Deep learning-PBL for heat transfer: Cultivating adaptive critical thinking and climate literacy

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Abstract

Global warming and the escalating climate crisis necessitate a paradigm shift in science education, moving beyond rote conceptual mastery toward fostering climate literacy and adaptive critical thinking, essential competencies for sustainable decision-making. This study investigates the impact of a Deep Learning-integrated Problem-Based Learning (DL–PBL) model within heat transfer instruction on developing adaptive critical thinking skills among elementary school students, from which contextualized climate literacy is systematically mapped and evaluated. Utilizing a quasi-experimental research framework with a non-equivalent control group pretest–posttest design, this study engaged 50 fourth-grade students. The experimental group received the DL–PBL intervention, which anchors instructional delivery in mindful, joyful, and meaningful learning principles, while the control group followed conventional instruction. Data collection relied on a validated critical thinking instrument contextualized within thermal physics phenomena and global warming scenarios. Statistical analysis indicated that the experimental group achieved significantly higher post-test scores ($M = 81.6$) than the control cohort ($M = 64.4$; $p < 0.001$). The most substantial improvements occurred within the Clarifying and Interpretation and Inference domains. The primary novelty of this study lies in its innovative reframing of classical critical thinking indicators into specialized, "adaptive" competencies, providing an empirical model where action-oriented climate literacy is directly evaluated through the student's capacity to decode thermal data and formulate concrete mitigation strategies. Ultimately, this research demonstrates that the unified DL–PBL model serves as a transformative framework for bridging abstract physics education with Education for Sustainable Development (ESD), offering a strategic pathway toward realizing Sustainable Development Goals 4 and 13 at the primary education level.

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1. Introduction

The intensifying global climate crisis has transformed from a distant environmental concern into an immediate pedagogical challenge, necessitating a fundamental reassessment of science education frameworks. As the world confronts unprecedented temperature anomalies and ecological shifts, the role of primary education in cultivating climate-ready citizens becomes paramount (Brosch, 2021). However, traditional science instruction, particularly regarding physical concepts like heat transfer, often remains siloed within theoretical boundaries, failing to bridge abstract physics with the socio-scientific realities of global warming. In the Indonesian context, characterized by high tropical climate vulnerability, an instructional shift is critically needed to foster conceptual mastery, adaptive critical thinking, and climate literacy simultaneously. Heat transfer comprising conduction, convection, and radiation is the fundamental physical mechanism driving the greenhouse effect and global temperature rise (Ayu, Damayanti, et al., 2025). Despite its direct relevance, elementary students frequently perceive these thermal concepts as disconnected from their environmental realities. Literature suggests that conventional pedagogical approaches prioritize rote memorization over deep conceptual integration, resulting in low student engagement and a deficit in actionable mitigation literacy (Hsu et al., 2024). To resolve this instructional mismatch, the Deep Learning paradigm characterized by mindful, joyful, and meaningful engagement offers a promising pathway. When integrated with Problem-Based Learning (PBL), this combined model transforms the classroom into an active laboratory for resolving real-world ecological challenges (Prastiyan et al., 2023).

To establish a rigorous pedagogical framework, this study anchors climate literacy within the foundational laws of thermal physics, positioning heat transfer education as a mechanistic conduit for environmental comprehension. Anthropogenic climate change is fundamentally a macroscopic consequence of global thermodynamic disequilibrium, driven by alterations in the Earth's energy balance. Consequently, the core

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mechanisms of physical heat transfer serve as the precise scientific variables governing greenhouse gas dynamics, global temperature rise, and atmospheric circulation patterns. By dissolving the traditional boundaries between abstract physics and environmental education, this approach transforms heat transfer instruction into a strategic entry point for functional climate literacy. Under this unified framework, students transition from a superficial awareness of climate anomalies toward a structurally grounded understanding of how micro-level thermal behaviors directly dictate macro-level ecological systems, thereby cultivating the empirical reasoning necessary for sustainable action-readiness.

To guide this investigation, this study explicitly distinguishes adaptive critical thinking from conventional critical thinking frameworks. While conventional frameworks typically evaluate static arguments from context-neutral textual prompts, adaptive critical thinking represents a dynamic, context-dependent cognitive capacity that enables learners to flexibly recalibrate their analytical strategies when confronting fluid socio-scientific crises. Within this pedagogical framework, standard critical thinking indicators problem formulation, data utilization, and inference are systematically reframed into specialized, adaptive competencies. Consequently, this approach shifts the educational focus from abstract logic toward requiring students to decode volatile thermal data, critique energy conservation claims, and negotiate environmental trade-offs to synthesize viable, localized climate mitigation strategies.

The primary novelty of this study lies in its systematic integration of the Deep Learning–Problem Based Learning (DL–PBL) model to recontextualize abstract heat transfer principles as strategic conduits for climate literacy and adaptive critical thinking at the primary education level (Suhada et al., 2024). While prior literature predominantly treats critical thinking as a generic, context-neutral skill, this research reframes analytical indicators, such as problem formulation, argument analysis, and inference into specialized, adaptive competencies required to interpret localized thermal anomalies (Suwandi et al., 2024). Consequently, this investigation directly fills the empirical gap by evaluating how primary science instruction can move beyond conceptual factual transmission to cultivate action-oriented climate resilience in line with global sustainability frameworks.

This study aims to fill this void by examining the role of the DL–PBL model in fostering climate literacy and adaptive critical thinking among fourth-grade students. By utilizing authentic climate stimuli, such as regional temperature anomaly data, the intervention seeks to contextualize heat transfer mechanisms within the framework of Sustainable Development Goals (SDG 4: Quality Education and SDG 13: Climate Action). It is hypothesized that a mindful and joyful integration of climate issues into the physics curriculum will not only enhance students' analytical rigor but also empower them to become proactive agents of sustainability (Dul Aji et al., 2024).

2. Method

2.1. Research Design

This study employed a quasi-experimental approach, specifically utilizing the non-equivalent control group pretest-posttest design (Plomp & Nieveen, 2013). This framework was selected to evaluate the causal impact of the Deep Learning-Problem Based Learning (DL–PBL) model within an authentic classroom environment where true randomization was not feasible. By comparing an experimental group with a control group while controlling for initial cognitive baselines via pre-tests, this design ensures a robust assessment of instructional efficacy on students' adaptive critical thinking. The flowchart of this research is shown by Figure 1.

2.2. Participants and Sampling

The study involved a cohort of 50 fourth-grade students (N=50) from an Indonesian primary school, recruited through purposive sampling. The selection criteria prioritized academic homogeneity and the developmental readiness of the participants regarding heat transfer concepts. The subjects were categorized into two distinct groups: the experimental group (n=25), which received the DL–PBL intervention, and the control group (n=25), which followed a conventional teacher-centered instructional model. Ethical clearance and informed consent were secured from both school authorities and parents prior to the commencement of the study (Ain, 2021).

2.3. Instructional Intervention (DL-PBL Syntax)

The experimental intervention followed a systematic four-stage DL–PBL syntax recontextualized for climate literacy. (1) Mindful Orientation, Students were exposed to regional temperature anomaly heatmaps to foster emotional engagement and awareness of global warming. (2) Collaborative Investigation, Groups explored the mechanisms of conduction, convection, and radiation as the physical drivers of the greenhouse effect. (3) Joyful Problem Solving, Students collaboratively designed creative climate adaptation models, such as energy-efficient insulators, emphasizing a positive learning atmosphere. (4) Reflective Evaluation, This final stage focused on peer-reviewing solutions and solidifying personal "eco-action" commitments (Ali et al., 2024). The process culminated in structured group presentations and metacognitive reflections, allowing students to internalize their evolving understanding of heat transfer and climate action, thereby systematically fostering adaptive critical thinking and climate literacy from an early age(Andersen, 2017).

2.4. Research Instruments

Data were collected using a Contextualized Adaptive Critical Thinking Test, consisting of 10 essay items framed within everyday thermal phenomena and socio-scientific climate issues. The instrument targeted five core indicators: problem formulation, data utilization, argument analysis, result evaluation, and inference. The psychometric integrity of the test was established through expert content validation (Aiken's V > 0.85) and demonstrated high internal consistency through Cronbach's Alpha ($\alpha = 0.82$). This study specifies that climate literacy was operationally inferred through contextualized adaptive critical thinking assessments rather than being evaluated via a separate, standalone instrument. Action-oriented climate literacy is conceptualized not as passive factual recall, but as the functional capacity to deploy thermal physics concepts when confronting real-world environmental disruptions. Therefore, the primary assessment mechanism relied on reframing core critical thinking indicators within explicit climate stimuli. For instance, the indicator of Clarifying and Interpretation was operationalized as the student's capacity to decode localized temperature anomaly heatmaps, while Inference and Argument Analysis were measured through the students' ability to synthesize viable thermal insulation models and critique energy conservation claims. Consequently, by assessing these specialized cognitive adaptations, the instrument directly mirrors and evaluates the functional, science-based dimensions of student climate literacy.

2.5. Data Analysis Techniques

Statistical analysis was performed using SPSS to test the research hypotheses. Following the verification of normality (Shapiro-Wilk) and homogeneity (Levene's test), an Independent Sample T-Test was conducted to determine significant differences between groups. Furthermore, the Normalized Gain (N-Gain) was calculated to quantify the magnitude of skill improvement (Cohen et al., 2018). To evaluate the practical significance of the DL–PBL model, the Effect Size was measured using Cohen's d, ensuring that the findings reflect both statistical significance and substantial educational

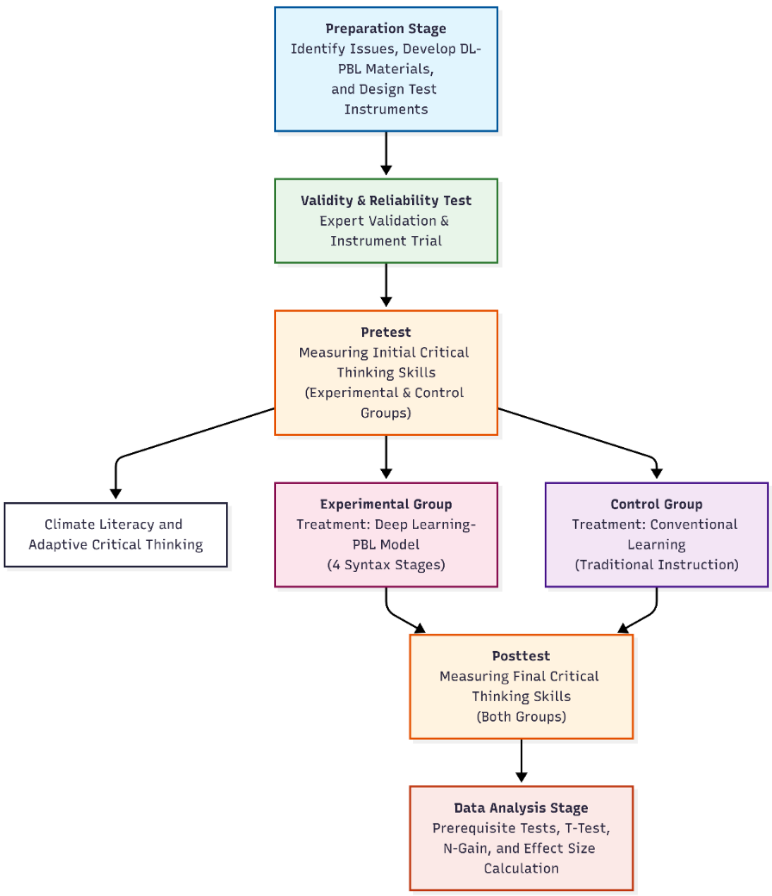

Figure 1. Research Methods

2.6. Research Instrument and Indicator Mapping

The primary assessment tool employed in this study was a contextualized critical thinking test developed based on the framework by Ayu et al (2024), encompassing four core indicators: Inference, Clarifying and Interpretation, Analyze and Evaluate Arguments, and Explanation (Ayu, Jufriadi, et al., 2025). The instrument consisted of ten structured essay items, specifically designed to evaluate students' reasoning within everyday heat transfer phenomena. Empirical validation was established using Pearson's Product-Moment correlation, yielding coefficients ranging from 0.433 to 0.734, which significantly exceeded the r-table threshold of 0.396. Furthermore, reliability testing using Cronbach's Alpha resulted in a coefficient of 0.693 (> 0.60), confirming the instrument's internal consistency and its robustness for measuring critical thinking in this specific domain.

In the theoretical framework of this study, these critical thinking indicators were systematically reframed as components of adaptive critical thinking to assess climate literacy. The capacity for Clarifying and Interpretation was operationalized as the student's ability to identify localized climate issues from thermal phenomena. Data utilization was interpreted as the proficiency in employing empirical evidence such as experimental temperature results and material thermal efficiency to assess claims regarding global warming. Moreover, the indicators of Inference, Analyzing Arguments, and Evaluating Results were mapped as the ability to construct causal explanations for environmental changes, distinguish scientific evidence from misconceptions, and evaluate the feasibility of proposed mitigation and adaptation strategies. Consequently, while formally structured as a critical thinking assessment, the instrument functions as a strategic indicator of climate literacy, requiring students to bridge physical energy concepts with global sustainability practices in their daily lives.

2.7. Data Analysis Techniques

The data analysis process in this study commenced with the systematic processing of pre-test and post-test scores for adaptive critical thinking from both the experimental and control groups. Descriptive statistics were initially computed to determine the minimum and maximum values, mean scores, and standard deviations for each cohort. Prior to hypothesis testing, the data were subjected to rigorous statistical assumption checks, including the Shapiro–Wilk test for normality and Levene's test for homogeneity of variance. These procedures ensured that the data distributions met the requirements for parametric analysis. To establish the equivalence of initial cognitive baselines, an Independent Samples T-Test was performed on the pre-test scores.

Furthermore, the primary evaluation of the DL–PBL intervention's efficacy involved an Independent Samples T-Test on the post-test scores of both groups, while a Paired Samples T-Test was applied within each group to measure the significance of longitudinal progress from pre-test to post-test at a 0.05 significance level. To provide a granular understanding of the treatment's impact, a detailed sub-indicator analysis was conducted. This involved comparing the mean scores of specific critical thinking components problem formulation, data utilization, inference, argument analysis, and result evaluation between the experimental and control groups. This comparative approach facilitated the interpretation of developmental patterns in adaptive critical thinking and identified emergent indicators of climate literacy resulting from students' engagement with heat transfer and global warming socio-scientific issues.

3. Results and Discussion

Figure 2 illustrates the integrated syntax of the Deep Learning-Problem Based Learning (DL–PBL) model, specifically designed to bridge heat transfer education with climate literacy (Hariyanto et al., 2023). The instructional sequence is structured into four transformative stages that facilitate a deep cognitive and emotional connection to socio-scientific issues. The process begins with (1) Mindful Orientation, where students are exposed to climate change stimuli and thermal phenomena to cultivate environmental empathy and situational awareness. This is followed by (2) Collaborative Investigation, characterized by data-driven inquiry where groups analyze empirical evidence, such as regional temperature heatmaps, to establish rigorous conceptual links between physics and climate reality. The third stage, (3) Joyful Problem Solving, empowers students to apply their critical reasoning through the creative modeling of adaptation and mitigation solutions within a positive, collaborative atmosphere. The cycle culminates in (4) Reflective Evaluation, a metacognitive phase involving peer review and a commitment to personal 'eco-actions.' Collectively, this syntax demonstrates a robust pedagogical framework that redefines science instruction as a vehicle for fostering adaptive critical thinking and proactive sustainability competencies in primary education.

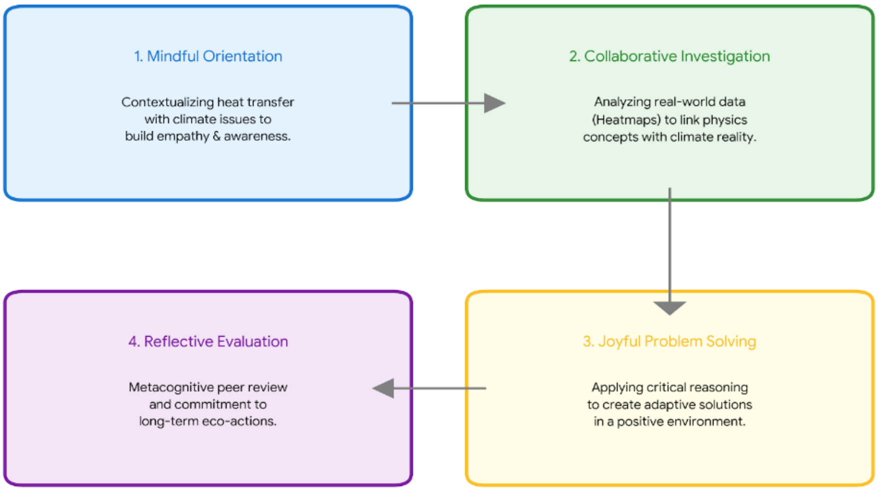

Figure 2. The Four Pillars of DL-PBL Instruction Syntax

3.1. Comparison of Pre-test and Post-test Scores

The assessment of adaptive critical thinking skills in this study is reflected in the comparison of pre-test and post-test scores between the experimental group (DL–PBL) and the control group (conventional instruction). At the onset of the intervention, both groups demonstrated relatively equivalent baseline competencies. The control group had a mean score of 46.0 (SD = 14.14, range 20–70), while the experimental group averaged 41.6 (SD = 12.81). An independent samples t-test confirmed no significant difference between the two groups ($p = 0.255$), establishing a comparable initial cognitive baseline. Following the intervention, the control group achieved a post-test mean of 64.4 (SD = 13.25). In contrast, the experimental group showed a substantially higher improvement, reaching a mean score of 81.6 (SD = 11.43) with scores ranging from 60 to 100. A post-test t-test analysis revealed a highly significant statistical difference ($p < 0.001$), with a mean difference of 17.2 points. Furthermore, the calculated Cohen's d of 1.26 indicates that the DL–PBL model has a very large effect size on enhancing students' critical thinking quality. The distribution of Normalized Gain (N-Gain) scores in Figure 3 and Figure 4, as illustrated in the box-and-whisker plot, provides a robust visualization of the learning growth disparity between the two cohorts. The data points, superimposed as a swarm plot, reveal the individual performance density within each group.

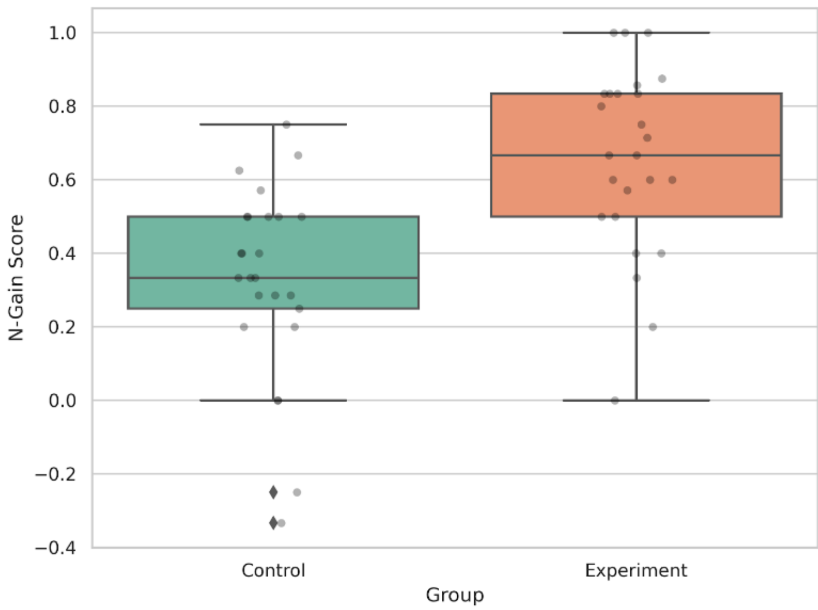

Figure 3. Normalized Gaind (N-Gain) Distribution

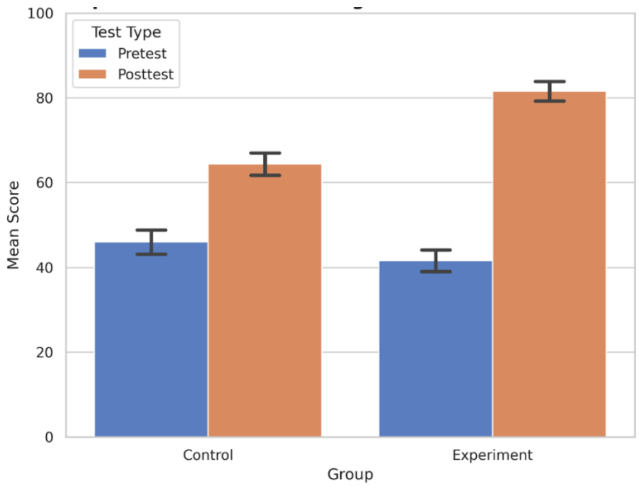

Figure 4. Comparison of Critical Thinking Pretest and Postest Scores

The experimental group, which underwent the DL–PBL intervention, exhibits a substantially higher and more concentrated gain distribution compared to the control group (Ayu et al., 2024). The median N-Gain for this group is positioned significantly above 0.6, falling within the "High" effectiveness category. The interquartile range (IQR) for the experimental cohort is situated predominantly between 0.5 and 0.8, indicating that the majority of students achieved a robust mastery of adaptive critical thinking skills through the mindful and joyful integration of climate-related heat transfer problems. Conversely, the control group demonstrates a lower median N-Gain, centered approximately at 0.3, which categorizes the instructional impact as "Moderate to Low". The wider spread of data points and the presence of outliers at the lower end including negative values indicating a lack of conceptual progress suggest that conventional teacher-centered instruction was less effective in fostering the cognitive flexibility required for adaptive reasoning (Purwaningsih et al., 2020). The clear separation between the two box plots, with minimal overlap in their respective IQRs, reinforces the statistical significance ($p < 0.001$) reported in the t-test analysis. This visual evidence directly supports the study's objective, confirming that the DL–PBL model serves as a superior pedagogical framework for bridging abstract physics concepts with functional climate literacy at the primary education level (Jarosievitz & Sükösd, 2023.).

3.2. Analysis of Critical Thinking Indicators Performance

The analytical results per indicator, as illustrated in Figure 5 and Figure 6, demonstrate that the DL–PBL model exerted a profound impact on the development of adaptive critical thinking, particularly in the Clarifying and Interpretation domain. The experimental group achieved a high N-Gain score of 0.80, significantly outperforming the control group, which only reached 0.36. This suggests that the systematic integration of temperature heatmaps as a mindful stimulus effectively empowered students to clarify complex environmental data and identify the core physical mechanisms underlying climate issues. Substantial growth was also observed in Inference (N-Gain = 0.74) and Analyzing and Evaluating Arguments (N-Gain = 0.66), indicating that students became highly proficient at drawing logical conclusions for climate mitigation and evaluating the scientific validity of environmental claims. While the Explanation indicator showed the least relative gain (0.53), it remained significantly higher than the control group's performance (0.31), showcasing a comprehensive improvement across all critical thinking sub-domains.

Complementing these findings, Figure 5 provides a comparative visualization of the mean score progression from pre-test to post-test for both cohorts. Initially, both groups demonstrated equivalent cognitive baselines across all four indicators, with pre-test scores hovering between 40.0 and 47.0. However, following the intervention, the experimental group showed dramatic vertical shifts in performance. The most striking improvement was recorded in Clarifying and Interpretation, where the mean score soared from 40.0 to 88.0. Similarly, significant post-test peaks were observed in Inference (85.0) and Argument Analysis (80.0), whereas the control group's post-test scores remained restricted within the 62.0–66.0 range. This marked divergence, evidenced in both figures, corroborates the hypothesis that the DL–PBL framework serves as a transformative pedagogical pathway for cultivating the 'adaptive' competencies necessary for interpreting thermal phenomena and responding to the global climate crisis (Moseley et al., 2020).

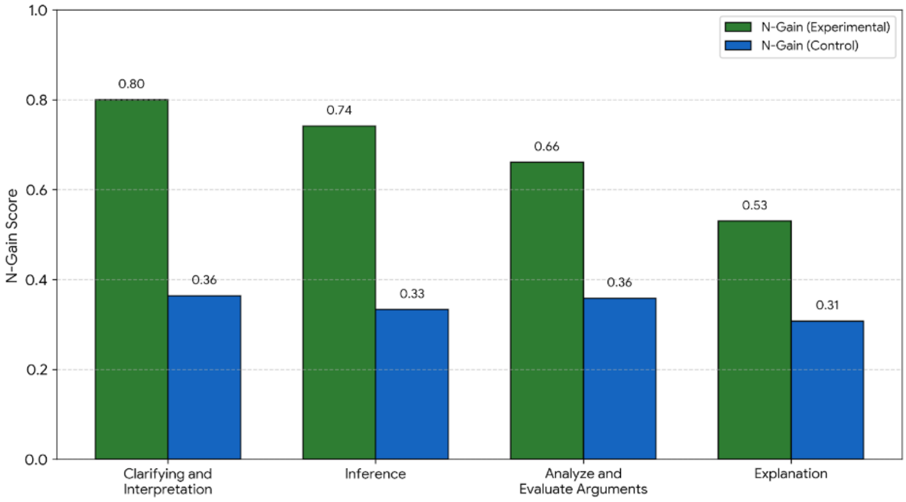

Figure 5. Normalized Gain (N-Gain) by Critical Thinking Indicator

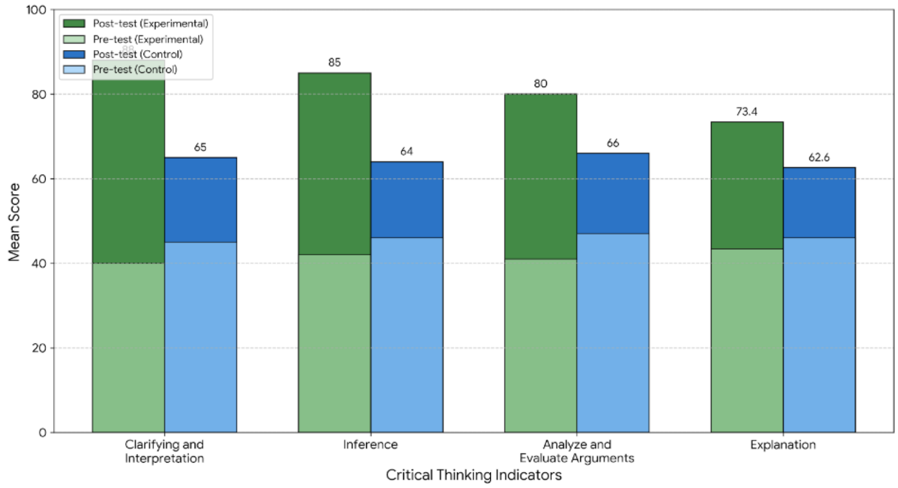

Figure 6. Comparison of Critical Thinking Skills Indicators: Pre-test and Post-test

The analysis of individual indicators suggests that the DL–PBL model does not merely increase total scores but fundamentally refines the quality of student reasoning toward "adaptive" critical thinking. The most significant disparity was observed in the Problem Formulation indicator, with a 38-point difference between groups. This demonstrates that students in the DL–PBL classroom are far more proficient at identifying the core issues within complex heat transfer scenarios and linking them to broader environmental warming. The indicators for Data Utilization and Argument Analysis showed an improvement margin of 22 points. This indicates that students moved beyond simple information gathering; they learned to select relevant evidence, verify the consistency of peer explanations, and critique claims regarding energy conservation and heat reduction. Meanwhile, gains in Evaluating Results (14-point difference) and Drawing Inferences (12-point difference) suggest that students became more adept at weighing the trade-offs of various solutions and making conclusions that consider long-term consequences a hallmark of adaptive cognition in the context of dynamic climate issues (Aji et al., 2024).

3.3. Emergence of Climate Literacy

The development of climate literacy is evidenced by the students' ability to bridge physical heat transfer concepts with sustainability practices. In written discussions, the DL–PBL group did not only explain temperature differences across surfaces (conductors vs. insulators) but proactively connected these to urban heat island effects, thermal comfort via ventilation, and the subsequent impact on household energy consumption (Guisasola & Zuza, 2021).

When tasked with formulating solutions, students proposed concrete "eco-actions" such as reforestation, utilizing high-albedo roofing, and optimizing electricity use. They justified these actions by explaining how local thermal management contributes to global warming mitigation. This pattern signifies the emergence of action-oriented climate literacy, where students transition from knowing "the Earth is warming" to understanding the causal links between local thermal behavior and global climate systems.

The analytical results per indicator, as illustrated in Figure 5, demonstrate that the DL-PBL model has the most profound impact on Clarifying and Interpretation skills (N-Gain = 0.80). This suggests that the use of temperature heatmaps as a mindful stimulus successfully enabled students to clarify complex environmental information. Furthermore, the significant growth in Inference (N-Gain = 0.74) indicates that students were able to draw logical conclusions about climate mitigation based on heat transfer principles. While Explanation showed the least relative impact compared to other indicators, it still achieved a moderate gain (0.53), significantly higher than the control group, showcasing a comprehensive improvement in all critical thinking domains.

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3.4. Indicators of Emerging Climate Literacy

The development of climate literacy in this study is evidenced by the students' emerging ability to synthesize heat transfer concepts with global warming phenomena and localized sustainability practices. Analysis of classroom discussions and written responses revealed that students in the DL–PBL cohort moved beyond basic identification of thermal variables such as temperature differentials between light and dark surfaces, shaded versus unshaded areas, or conductors and insulators. Instead, they proactively correlated these physical principles with broader environmental realities, such as the mechanisms behind urban heat islands, the role of ventilation in thermal comfort, and the subsequent impact on household energy consumption and air conditioning usage (Hudha et al., 2023).

When prompted to formulate mitigation strategies, a significant number of students proposed concrete, science-based "eco-actions," including urban reforestation, the application of high-albedo (light-colored) roofing, the use of thermal barriers, and the reduction of unnecessary electricity consumption. Critically, students provided reasoned justifications for these actions, explaining how localized thermal management directly contributes to broader global warming mitigation efforts. This pattern signifies the emergence of action-oriented climate literacy. Students demonstrated a transition from passive factual knowledge (e.g., "the Earth is warming") toward a functional understanding of the causal links between local thermal behavior, energy consumption, and global climate systems. Such competencies align with the core characteristics of climate literacy defined within the frameworks of Climate Change Education and Education for Sustainable Development (ESD).

Figure 7 displays a Global Temperature Anomaly Heatmap (1900–2023), illustrating a profound longitudinal shift in global climate patterns. The visualization utilizes a color-coded gradient where blue represents temperatures below the 0°C baseline and red indicates positive anomalies. A clear transition is observable from the mid-20th century, where the cooling trends of the early 1900s are replaced by a rapid and consistent warming trajectory. This global context is essential for fostering students' situational awareness, providing a macro-level justification for studying heat transfer as the physical mechanism driving these unprecedented anomalies.

Complementing this global perspective, Figure 8 provides a localized Heatmap of Annual Average Temperature Anomalies in Indonesia (2000–2023) across major regions, including Sumatera, Jawa, Kalimantan, Sulawesi, Maluku, Papua, and Bali-Nusa Tenggara. The data reveals that localized warming has intensified significantly since 2015, with anomaly values frequently exceeding 1.0 °C by 2023. This regional data serves as an authentic socio-scientific stimulus, enabling students to connect conduction, convection, and radiation concepts to their immediate geographical reality. By analyzing these specific heatmaps, students in the experimental group were empowered to clarify complex environmental information and formulate adaptive solutions, directly fulfilling the study’s objective of fostering functional climate literacy and adaptive critical thinking.

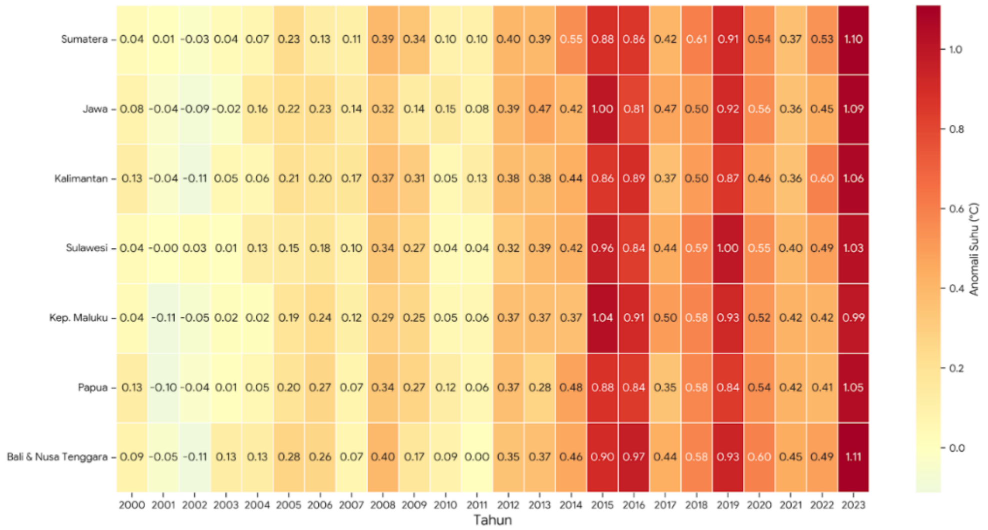

Figure 7. Indonesia Temperature Anomaly Heatmap

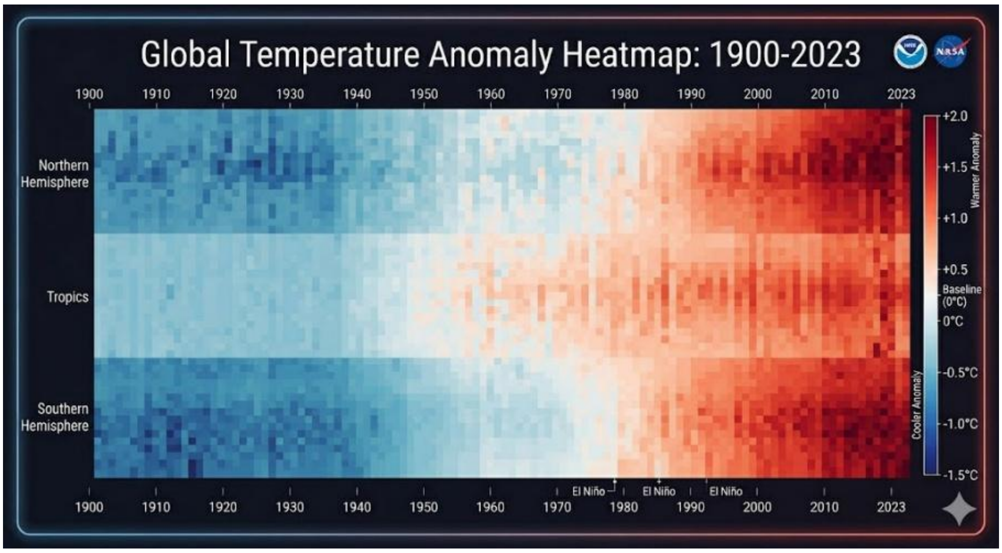

Figure 8. Global Temperature Anomaly Heatmap

3.5. The Efficacy of DL–PBL in Cultivating Adaptive Critical Thinking

The finding that the DL–PBL model generates a statistically significant increase in students' critical thinking capacity aligns with global empirical evidence. International literature consistently identifies Problem-Based Learning (PBL) as a potent pedagogical tool for developing higher-order thinking skills, including analysis, evaluation, and problem-solving across diverse scientific and environmental contexts (Purwaningsih et al., 2020). In this study, the integration of Deep Learning principles specifically joyful, mindful, and meaningful engagement further amplifies the efficacy of PBL by positioning emotional involvement and metacognitive reflection at the core of the learning experience as shown by Table 1.

Specifically, the marked improvements in the indicators of Problem Formulation and Argument Analysis demonstrate that the DL–PBL syntax, which initiates with authentic socio-scientific issues and culminates in reflective evaluation, compels students to actively define problems rather than merely executing prescribed tasks. This is consistent with the theoretical perspective that deeply designed problem-based instruction shifts the student's role from a passive recipient to an adaptive problem solver. Such learners are capable of adjusting their cognitive strategies in response to dynamic information and evolving environmental scenarios (Dul Aji et al., 2023).

Table 1. Mapping of DL–PBL Learning Stages to Adaptive Critical Thinking Indicators in Heat Transfer Education

Stage (Syntax)	Teacher's Role	Student's Role	Climate-Based Critical Thinking Indicators
Mindful Orientation to Climate Issues	Presenting global warming stimuli (videos/news) using a mindful approach to cultivate environmental empathy.	Observing phenomena and reflecting on the emotional and social impacts of the climate crisis.	Analysis: Identifying core arguments and correlating climate issues with daily life.
Collaborative Investigation of Data	Facilitating group investigations using authentic data (e.g., Indonesian temperature anomaly heatmaps) and heat transfer concepts.	Analyzing data and linking conduction, convection, and radiation mechanisms to global warming processes.	Analysis & Evaluation: Assessing data credibility and evaluating potential biases in climate information.
Joyful Problem Solving & Modeling	Encouraging creative and joyful collaboration in designing adaptation models (e.g., energy-efficient housing designs).	Engaging in discussions, developing solution prototypes, and presenting them through a positive problem-solving lens.	Inference: Drawing logical conclusions and proposing science-based innovative solutions.
Reflective Evaluation & Eco-Action	Leading reflections on the effectiveness of developed solutions and fostering commitment to "eco-actions".	Evaluating peer arguments, reflecting on the learning journey, and planning real-world actions in school or home environments.	Evaluation & Inference: Assessing the strength of proposed solutions and formulating sustainable action plans.

The results of this study reinforce the argument that fundamental concepts of energy and energy transfer specifically heat, radiation, and energy balance are pivotal in constructing climate literacy. By correlating elementary physical phenomena, such as surface temperature differentials, the application of conductors and insulators, and indoor air circulation, with the broader issue of global warming, students are able to develop a progressive understanding of how alterations in Earth's energy systems trigger global temperature rises.

Current research in climate change education suggests that instructional approaches linking core scientific concepts with localized experiences and daily actions are significantly more effective in enhancing climate literacy and "action-readiness" compared to the isolated teaching of climate facts. Within this framework, heat transfer functions as a critical "conceptual bridge" that connects micro-level observations within the student's immediate environment such as the classroom or schoolyard to the macro-level dynamics of the global climate system. Consequently, this pedagogical alignment resonates deeply with the principles of Education for Sustainable Development (ESD) and the targets set by SDG 13 (Climate Action).

The integration of joyful, mindful, and meaningful dimensions within the DL–PBL design demonstrates a profound resonance with the established literature on deep meaningful learning and transformative education. Joyful exploratory activities generate positive emotional engagement, which is critical for enhancing conceptual retention and fostering openness toward complex global challenges such as global warming. Furthermore, mindful reflective practices enable students to monitor their own cognitive processes, identify deep-seated misconceptions, and develop a heightened sensitivity to the long-term environmental consequences of their daily choices. By ensuring the curriculum remains meaningful through the contextualization of heat transfer within real-world sustainability issues, the model facilitates the transfer of knowledge to novel situations and encourages more responsible decision-making.

Consequently, the application of the DL–PBL model in heat transfer education serves as a strategic micro-level implementation of Education for Sustainable Development (ESD). Within this framework, cognitive competencies (physics concepts), affective domains (climate awareness), and metacognitive skills (critical reflection) are developed simultaneously through an integrated and holistic learning experience. This synergy effectively reimagines physics education not merely as the transmission of facts, but as a primary vehicle for fostering climate resilience and proactive sustainability competencies (Aji, Ayu, et al., 2025).

3.6. Implications and Contributions

Theoretically, this study expands the framework of physics education by explicitly positioning climate literacy and adaptive critical thinking as primary outcomes of heat transfer instruction. This contributes to a paradigm shift from treating physics as isolated conceptual content toward viewing it as a strategic lens for sustainability. This shift aligns with international research trends that utilize empirical science education to enhance students' understanding of Earth's thermal dynamics. Practically, the findings demonstrate that primary science educators can design effective heat transfer units that simultaneously foster SDG competencies. This is achieved through: (1) selecting problem contexts linked to local climate issues, (2) utilizing PBL syntax that explicitly directs students toward mitigation and adaptation analysis, and (3) integrating joyful, mindful, and meaningful deep learning strategies (Suhada et al., 2024).

At the macro-policy level, these results suggest that national curriculum guidelines should explicitly encourage instructional models that link energy concepts with global warming and SDG 13, rather than focusing solely on factual mastery. This repositioning can be realized by incorporating climate literacy and adaptive critical thinking as key learning outcomes in science standards and assessments. From a curricular perspective, schools and developers must provide institutional support for teachers to adopt the DL–PBL model (Ayu et al., 2022). This includes providing authentic lesson units, teaching materials, and assessments centered on contextual problems such as energy consumption and practical mitigation strategies. Furthermore, teacher training programs must equip educators with the pedagogical competence to facilitate joyful, mindful, and meaningful discussions on climate issues that are scientifically rigorous yet context-sensitive (Aji, Jemat, et al., 2025).

While the empirical data generated in this study primarily stem from direct measurements of students' adaptive critical thinking capacities, these cognitive outcomes serve as a robust operational proxy for emerging climate literacy. It is critical to note that this investigation did not employ a separate, standalone instrument dedicated exclusively to affective or factual climate knowledge. Instead, actionable climate literacy was systematically evaluated through the recontextualization of standard critical thinking indicators within real-world thermal physics scenarios. Consequently, the substantial improvements observed in the experimental group's ability to decode localized temperature anomalies, critique energy efficiency claims, and evaluate mitigation trade-offs are interpreted as vital conceptual components of functional climate literacy. Rather than claiming an exhaustive measurement of all climate literacy dimensions, these results demonstrate that the DL–PBL framework equips learners with the necessary analytical competencies to respond adaptively to environmental crises. Therefore, the cultivation of advanced climate literacy should be understood as a profound teoretis and practical implication of fostering adaptive critical thinking within contextualized science education.

The primary novelty of this research lies in re-positioning heat transfer not merely as a physics topic, but as a strategic entry point for fostering action-oriented climate literacy at the elementary level (Ain, 2017). Classical critical thinking indicators formulating problems, utilizing data, analyzing arguments, evaluating results, and drawing inferences are reframed as "adaptive" competencies used to interpret and respond to daily thermal-related climate challenges. This effectively bridges the gap between physics education, Education for Sustainable Development (ESD), and SDG 13 (Climate Action). Practically, this study provides a replicable instructional blueprint complete with syntax, problem contexts, and indicator mapping to integrate sustainability into primary science education (Jufriadi et al., 2024).

4. Conclusion

This study demonstrates that the implementation of the Deep Learning–integrated Problem-Based Learning (DL–PBL) model in heat transfer education significantly enhances the adaptive critical thinking skills of elementary school students compared to conventional instruction (Ain & Rahutami, 2018). Statistical evidence reveals a substantial post-test mean difference of 17.2 points, with the most prominent improvements observed in problem formulation, data utilization, and argument analysis. The joyful, mindful, and meaningful learning experiences inherent in the DL–PBL framework facilitate active engagement, metacognitive reflection, and a profound connection between abstract physical concepts and global warming phenomena. By positioning heat transfer as a strategic entry point for climate literacy, this model effectively bridges the gap between physics education and Education for Sustainable Development (ESD) within the frameworks of SDG 4 (Quality Education) and SDG 13 (Climate Action). Ultimately, this approach empowers young citizens to become more environmentally sensitive and capable of critically reasoning toward adaptive local solutions for the escalating global climate crisis. Although this study demonstrates the efficacy of the DL–PBL model in physical science education, several pathways remain open for future investigation to extend these contributions. First, given the relatively small sample size ($N = 50$) restricted to a single primary school, future research should implement large-scale, multi-site longitudinal studies across diverse demographic regions to evaluate the structural generalizability and long-term retention of adaptive critical thinking skills. Second, because this investigation relied on an adaptive critical thinking instrument as an operational proxy for climate literacy, subsequent studies should develop and validate distinct, multi-dimensional assessment tools that explicitly isolate the affective, behavioral, and psycho-social dimensions of climate action readiness. Finally, future pedagogical frameworks could explore the integration of Adaptive Mobile-STEAM projects or hybrid interactive platforms to scale the DL–PBL syntax, thereby evaluating its cross-disciplinary adaptability to other core scientific domains facing fluid socio-scientific crises.

Author Contributions

Nurul Ain: Conceptualization, Methodology, Investigation, Resources, Formal analysis, Writing - Original draft, Writing - Review & editing. Hena Dian Ayu: Conceptualization, Methodology, Validation, Data curation, Visualization, Supervision, Writing - Review & editing.

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Declaration of Conflicting Interests

All the authors declare that there are no financial or personal relationships with other people or organizations that could inappropriately influence or bias the content of this work. Potential competing interests, including but not limited to employment, consultancies, stock ownership, honoraria, patent applications, or research grants, do not exist in relation to this study. Declarations of interest: none

Data Availability

The datasets generated during and/ or analyzed during the current study are available from the corresponding author on reasonable request.

Declaration on AI Use

The authors declare that no artificial intelligence (AI) or AI-assisted tools were used in the preparation of this manuscript.

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