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Enhancing Cognitive and Argumentation Skills through Integration of Argument-Driven Inquiry and the Scientific Method in Physics Education

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Abstract – *Developing students' cognitive abilities and scientific argumentation skills is critical in physics education, yet traditional teacher-centered approaches often fail to achieve these goals. This study investigates the impact of integrating the Argument-Driven Inquiry (ADI) model with the scientific method on students' conceptual understanding and argumentation quality. A quasi-experimental pretest–posttest control group design was employed involving 64 Grade XI science students from a senior high school in Palu, Indonesia. Participants were assigned to an experimental group (ADI + scientific method) and a control group (ADI only) through a cluster random sampling method. Both groups studied the topic of heat and temperature over three sessions. Cognitive ability was measured using a validated multiple-choice test targeting understanding (C2), application (C3), and analysis (C4), while argumentation skills were assessed using an open-ended test based on Toulmin's Argument Pattern. Results showed that the experimental group achieved higher normalized gains in cognitive ability (0.65, medium) compared to the control group (0.37, medium), and in argumentation skills (0.76, high) compared to 0.66 (medium). A strong positive correlation ($r = 0.61, p < 0.001$) was observed between cognitive and argumentation gains, indicating a reciprocal relationship. The novelty of this study lies in embedding scientific method phases into ADI's discourse structure, producing measurable synergy between conceptual and epistemic outcomes. The findings contribute to physics education by offering an empirically supported instructional model that fosters both content mastery and scientific reasoning, providing a framework for enhancing scientific literacy in secondary classrooms.*

Keywords: *argument-driven inquiry; cognitive abilities; physics education; scientific argumentation skills; scientific method*

I. INTRODUCTION

Physics education occupies a central position in equipping students with the competencies necessary to understand and explain natural phenomena, while fostering the analytical mindset required for addressing complex real-world problems in the 21st century (Kamaluddin et al., 2023). As an essential component of science education, physics develops both conceptual knowledge and process skills, including critical thinking, reasoning, and evidence-based decision-making. In today's rapidly evolving scientific and technological landscape, these skills are increasingly recognized as prerequisites for scientific literacy and active participation in a knowledge-driven society. Research consistently emphasizes that learning environments should cultivate not only mastery of facts and formulas but also the cognitive processes underpinning scientific inquiry (Kaçar, 2023; Zakirman et al., 2023).

Despite this recognition, persistent challenges remain in achieving these goals. Studies have shown that many physics classrooms still rely heavily on traditional lecture-based instruction, which privileges rote memorization and algorithmic problem-solving over reasoning and conceptual integration (Sani et al., 2025). While such approaches can efficiently transmit factual content, they often fail to engage students in the deeper cognitive work of hypothesis generation, model construction, and argumentation. This limitation is significant because the ability to construct and evaluate arguments from evidence is a hallmark of scientific thinking and a crucial skill for lifelong learning. Preliminary observations in several senior high schools in Palu City, Indonesia, conducted in early 2025, underscore this concern. Student performance in physics, especially in the topic of heat and temperature, revealed marked deficiencies: average achievement rates stood at 45% for recall-level questions (C1), 30% for comprehension (C2), 20% for application (C3), and only 10% for analytical thinking (C4). Teachers interviewed during this preliminary phase reported ongoing difficulties in guiding students from basic recall toward higher-order cognitive processes, citing a lack of opportunities for inquiry, experimentation, and structured discussion. Such findings align with trends observed in other national and international studies, where students demonstrate a limited ability to apply concepts in novel contexts or justify claims with evidence (Fuadah et al., 2023; Utami et al., 2024).

The central problem is that many students in physics classrooms are not developing the integrated skill set of cognitive mastery and scientific argumentation. This skill gap can be attributed to several interrelated factors: teacher-centered instruction, infrequent use of inquiry-based learning, and limited exposure to authentic scientific practices. In many cases, practical work is limited to one or two sessions per semester, significantly reducing students' opportunities to explore concepts through experimentation, data analysis, and collaborative reasoning. Without these opportunities, students are less likely to internalize the epistemic norms of science, such as evidence-based reasoning, hypothesis testing, and the iterative refinement of ideas (Parno et al., 2021; Karawahenni et al., 2024).

One promising avenue for addressing this problem is the integration of pedagogical models that actively engage students in constructing and defending their own explanations. Inquiry-based learning approaches have been shown to promote deeper conceptual understanding and foster the skills necessary for scientific reasoning (Kusumaningrum et al., 2017; Shofiyah et al., 2020). Within this broad category, scientific argumentation occupies a special role: it not only supports the learning of disciplinary content but also mirrors the authentic practices of the scientific community. According to Toulmin's (2003) framework, effective scientific argumentation requires the articulation of claims, the presentation of supporting data, the use of warrants and backing to justify the connection between data and claims, and the consideration of possible rebuttals.

A model that explicitly combines inquiry with structured argumentation is the Argument-Driven Inquiry (ADI) approach. ADI is designed to engage students in the full cycle of scientific investigation, from identifying research questions to presenting and defending conclusions (Baharsyah & Admoko, 2020; Rosidin et al., 2019). It promotes collaborative learning, where students construct arguments based on empirical evidence, critique the arguments of peers, and revise their own claims in light of new information. Research indicates that ADI can significantly improve both conceptual understanding and argumentation skills across various science domains (Amielia et al., 2018; Fakhriyah et al., 2021; Suganda et al., 2023). In parallel, the scientific method offers a complementary structure for inquiry. As a systematic process comprising observation, question formulation, hypothesis generation, experimentation, analysis, and conclusion it reinforces logical thinking and evidence-based reasoning (Nurhidayati et al., 2023; Putra et al., 2020). While the ADI model emphasizes discourse and social construction of knowledge, the scientific method provides a disciplined procedural backbone for inquiry.

Individually, both ADI and the scientific method have been validated as effective in promoting learning gains. However, there is comparatively little research on their combined application in physics education (Amelia et al., 2021; Satriya & Atun, 2024). Integrating these approaches has the potential to leverage their complementary strengths: ADI's emphasis on argumentation can deepen conceptual engagement, while the scientific method's procedural rigor can enhance the validity and reliability of student-generated knowledge claims. In addition, the relationship between cognitive ability and argumentation skill remains underexplored in the context of integrated instructional models. While some studies suggest that conceptual understanding is a prerequisite for effective argumentation (Parno et al., 2021; Pan et al., 2021), others indicate that the process of argumentation can itself promote cognitive growth by compelling students to articulate, defend, and refine their ideas (Pesonen, 2022; Santibáñez, 2024). This bidirectional relationship warrants empirical investigation, particularly in settings where instructional designs deliberately foster both domains.

The present study aims to address these gaps by investigating the impact of integrating the ADI model on students' cognitive abilities and argumentation skills in physics learning. Specifically, this study seeks to compare the effectiveness of the integrated ADI–scientific method approach with the ADI model alone in improving cognitive and argumentation outcomes. The novelty of this study lies in its focus on the synergistic effects of combining ADI with the scientific method, rather than treating them as separate pedagogical strategies. By embedding the procedural rigor of the scientific method within the socially interactive framework of ADI, the study proposes a model that not only enhances individual learning outcomes but also strengthens the interdependence between conceptual understanding and scientific reasoning. The findings are expected to contribute to both theory and practice in physics education by offering empirical evidence to support the design of instructional models that holistically develop students' cognitive and epistemic competencies.

II. METHODS

This study employed a quasi-experimental design with a randomized control group pretest–posttest format. This methodological approach is widely used in educational research to evaluate the causal effects of instructional interventions while accommodating constraints in randomizing individual participants (Fraenkel et al., 2012). The study was conducted during the second semester of the 2024/2025 academic year at a public senior high school in Palu City, Indonesia. The population consisted of all Grade XI science students enrolled in the selected school, and sampling was carried out using a cluster random sampling technique to ensure that intact classes were maintained during the study while preserving the equivalence of the groups before treatment (Fraenkel et al., 2012; Kaçar, 2023). Two classes (XI MIPA) were randomly selected from the population and then randomly assigned as the experimental group (n = 32) and the control group (n = 32), resulting in a total sample size of 64 students.

The experimental group received instruction using the ADI model, which was integrated with the scientific method, whereas the control group was taught using the same ADI model without the explicit incorporation of scientific method phases. The rationale for integrating these two approaches draws from research highlighting that ADI promotes student-led argument construction, peer critique, and iterative refinement of claims (Baharsyah & Admoko, 2020; Rosidin et al., 2019), while the scientific method provides a structured procedural framework for systematic investigation, hypothesis testing, and evidence-based reasoning (Kusumaningrum et al., 2017; Shofiyah et al., 2020). Combining these approaches was expected to reinforce both conceptual mastery and argumentation proficiency.

To ensure the comparability of the groups before the intervention, a pretest was administered to measure baseline cognitive ability and argumentation skills. The results were analyzed to confirm the absence of statistically significant differences between the groups, ensuring that any posttest differences could be attributed to the instructional treatment rather than to pre-existing disparities. Both groups were taught the same physics content over a three-week intervention period, specifically the topic of heat and temperature. In the experimental group, the lesson design explicitly embedded the phases of the scientific method problem formulation, hypothesis development, experimentation, analysis, and conclusion drawing within each stage of the ADI cycle. In contrast, the control group followed the standard ADI framework, emphasizing argumentation but without the procedural inquiry stages.

Four instruments were employed for data collection. The first instrument was a multiple-choice cognitive ability test targeting three cognitive levels of the Revised Bloom's Taxonomy: understanding (C2), applying (C3), and analyzing (C4). Each domain was operationalized according to Anderson and Krathwohl's (2001) taxonomy framework. The test was validated through expert review to ensure content validity, and statistical analyses were performed to determine reliability (Cronbach's alpha), difficulty index, and discrimination index. The same test functioned as both pretest and posttest. The second instrument was the argumentation skill test, designed based on Toulmin's Argument Pattern (Toulmin, 2003), which evaluated five key components of scientific argumentation: claim, data, warrant (justification), backing (support), and rebuttal. This instrument underwent expert validation, pilot testing, and subsequent refinement to ensure its appropriateness for the target population.

The third data source was the observation sheet, which documented the fidelity of implementation and classroom interactions during the intervention. Observers recorded indicators of student engagement, inquiry behaviors, and adherence to the designed instructional sequence. The final instrument was the student response questionnaire. This instrument was a Likert-scale survey administered to the experimental group to capture students' perceptions of the integrated learning approach. This was complemented by semi-structured interviews with a purposive subsample of six students (three from each group) to provide qualitative insights that supported the quantitative results.

For the analysis of cognitive and argumentation outcomes, normalized gain scores (g) were calculated using the formula proposed by Hake (1998). Gain scores were interpreted using the classification criteria provided in Table 1, where values of $g \geq 0.70$ indicate high gains, $0.30 \leq g < 0.70$ indicate moderate gains, and $g < 0.30$ indicate low gains. Table 1 thus served as a reference for evaluating the magnitude of the learning improvements observed in both groups.

Table 1. Normalized gain score classification

Category	Gain score
High	$g \geq 0.70$
Moderate	$0.30 \leq g < 0.70$
Low	$g < 0.30$

Inferential statistics were then used to test the study's hypotheses. Independent-samples t-tests were applied to determine whether posttest gains differed significantly between the experimental and control groups for both cognitive and argumentation measures. To examine the relationship between cognitive gains and argumentation gains, a Pearson correlation analysis was conducted, with interpretation of correlation strength following the categories in Table 2. Coefficients of 0.60–0.79 indicate a strong correlation, 0.40–0.59 a moderate correlation, and 0.00–0.19 a very weak correlation.

Table 2. Interpretation criteria for correlation coefficients

Interpretation	Correlation coefficients
Verry strong	0.80-1.00
Strong	0.60-0.79
Moderate	0.40-0.59
Very weak	0.00-0.19

The research procedure was systematically structured into three stages: preparation, implementation, and final evaluation, as illustrated in Figure 1. During the preparation stage, the research team conducted a literature review, curriculum analysis, and instrument validation. The implementation stage involved delivering the respective instructional treatments to the experimental and control groups, with continuous observation of classroom activities. The final stage encompassed post-testing, data processing, and statistical analysis, culminating in the interpretation of findings in relation to the study's objectives.

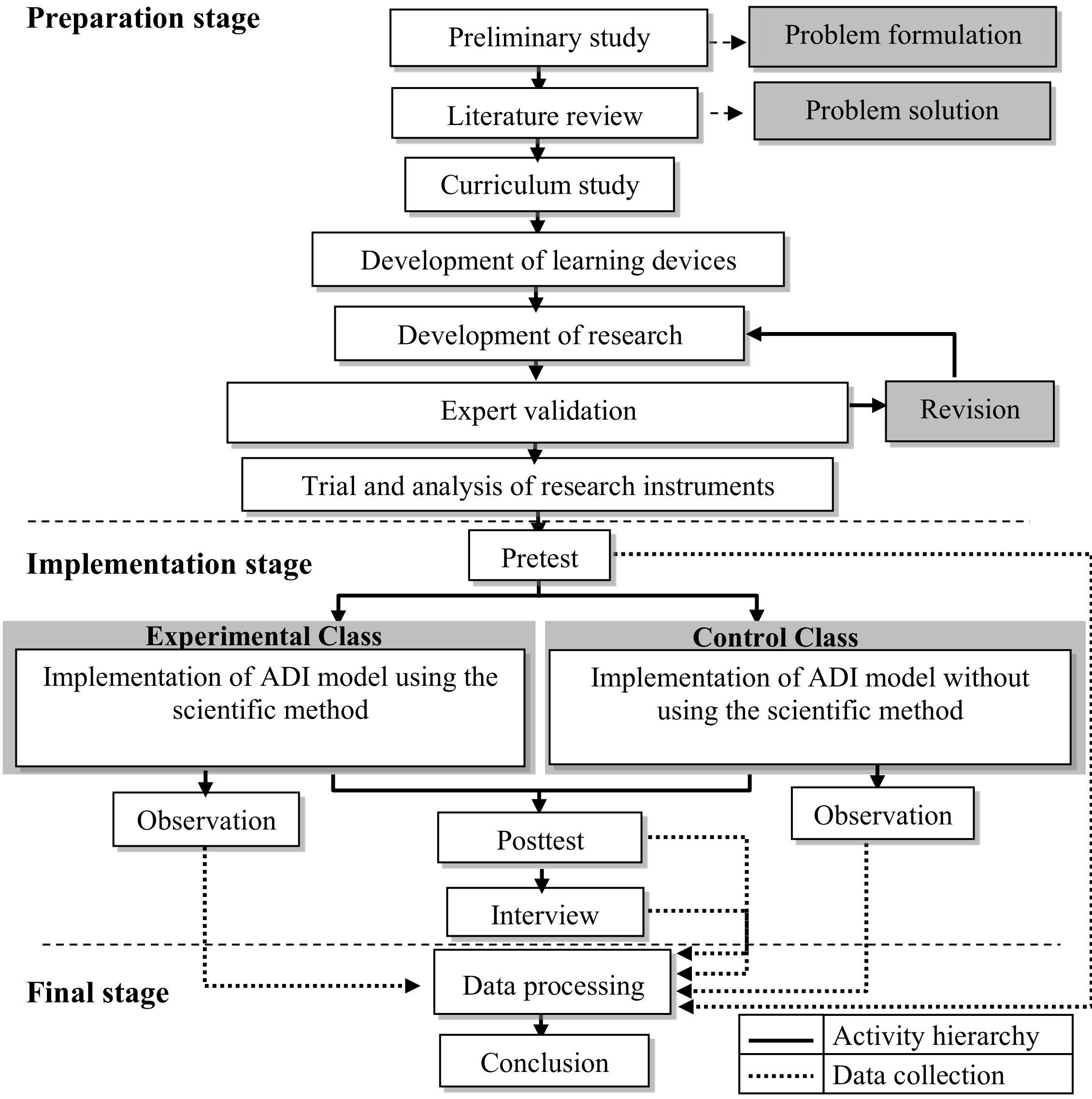

Figure 1. Research procedure flowchart

III. RESULTS AND DISCUSSION

The integration of the ADI model with the scientific method was implemented over three instructional sessions on the topic of heat and temperature. The intervention was explicitly designed to promote both cognitive development and scientific argumentation skills, aligning the phases of instruction with the Revised Bloom's Taxonomy for cognitive processes and Toulmin's Argument Pattern (TAP) for argumentation components. Table 3 presents the relationship matrix between each stage of the integrated instructional model, the corresponding phases of the scientific method, targeted cognitive competencies, and associated argumentation skills. The sequence progressed from concept introduction and problem identification through to argument refinement and conclusion, ensuring that students engaged in both conceptual and epistemic practices throughout the learning process.

Table 3. Relationship matrix between stages of ADI with the scientific method and expected competencies

Learning stage	Scientific approach	Cognitive competencies	Argumentation skills	Description
Stage I: Concept introduction, problem identification, questioning	Observation, question formulation	Understanding (C2)	Claim formulation	Students are introduced to core concepts of heat and temperature, identify problems, and formulate scientific questions. This stage activates prior knowledge and encourages curiosity.
Stage II: Constructing tentative arguments	Hypothesis development	Applying (C3)	Data presentation	Learners develop tentative arguments (claims) supported by initial evidence or reasoning, based on the hypotheses generated from the scientific inquiry process.
Stage III: Argument presentation and discussion	Experimentation, data collection, and analysis	Applying (C3), Analyzing (C4)	Justification, support	Students present their arguments, supported by experimental data, and justify their claims with logical reasoning. They engage in peer discussions to evaluate the strength of the evidence.
Stage IV: Argument refinement and conclusion	Conclusion drawing, critical evaluation	Analyzing (C4)	Rebuttal, argument refinement	Learners critically assess counterarguments, refine their arguments, and draw scientifically supported conclusions, enhancing both cognitive understanding and argumentation quality.

The analysis of cognitive learning outcomes is summarized in Figure 2, which compares the mean pretest, posttest, and normalized gain (g) scores for the experimental and control groups. Both groups began at statistically comparable baselines (0.42 vs. 0.33). Following the intervention, the experimental group achieved a higher mean posttest score (0.78) and normalized gain (0.65) compared to the control group (0.58; g = 0.37). While the (g) score for the experimental group fell within Hake's medium category, it approached the threshold for high gain ($g \geq 0.70$), indicating a substantial instructional effect.

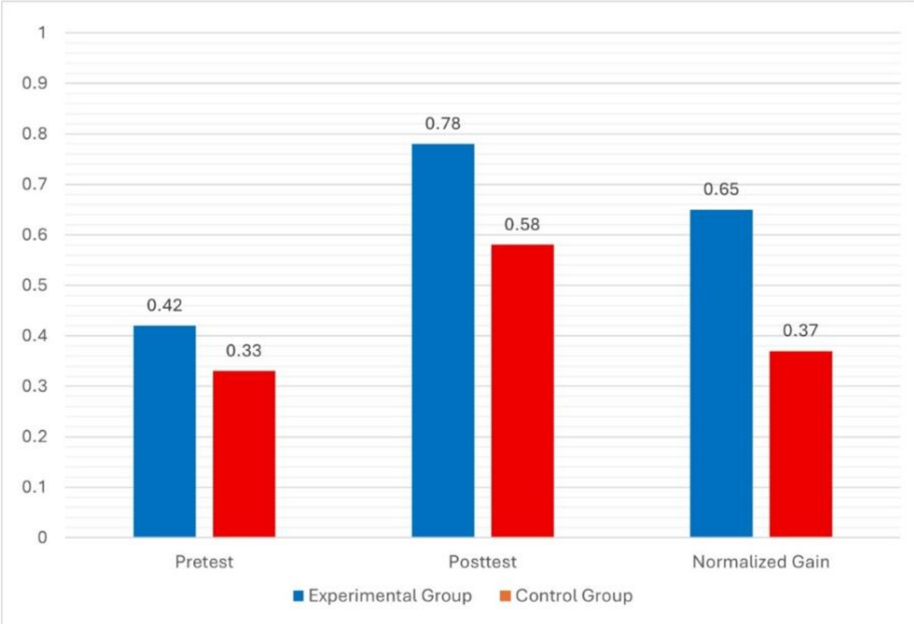

Figure 2. Comparison of pretest, posttest, and normalized gain ⟨g⟩ scores for cognitive outcome

Despite these positive results, the normalized gains did not reach the high category, warranting further interpretation. Classroom observations revealed that critical phases such as questioning and reasoning identified by Wieman (2007) as pivotal for conceptual change were not optimally enacted during the early sessions. This partial implementation likely constrained higher-order engagement, suggesting that the effectiveness of the integrated model is sensitive to its fidelity of delivery. As Arini (2020) notes, maximizing opportunities for reasoning is essential for enabling students to engage with and internalize scientific content fully.

From a theoretical perspective, the gains in cognitive performance can be explained through constructivist learning theory and Vygotsky's social development theory. The ADI framework encourages collaborative knowledge construction through discourse and peer critique. At the same time, the embedded scientific method stages provide scaffolding that allows learners to progress within their Zone of Proximal Development (ZPD). This scaffolding facilitates a gradual transfer of responsibility for learning from the teacher to the students, promoting autonomy in scientific inquiry.

The disaggregated normalized gains for the three targeted cognitive domains are presented in Figure 3. The most significant improvement in the experimental group occurred in understanding (C2) with a gain of 0.69, followed by application (C3) at 0.66, and analysis (C4) at 0.64. These results indicate that the instructional design effectively enhanced both fundamental conceptual grasp and higher-order thinking abilities. This finding aligns with Kaçar (2023), who reported that argument-based learning substantially supports deep and transferable conceptual understanding in science.

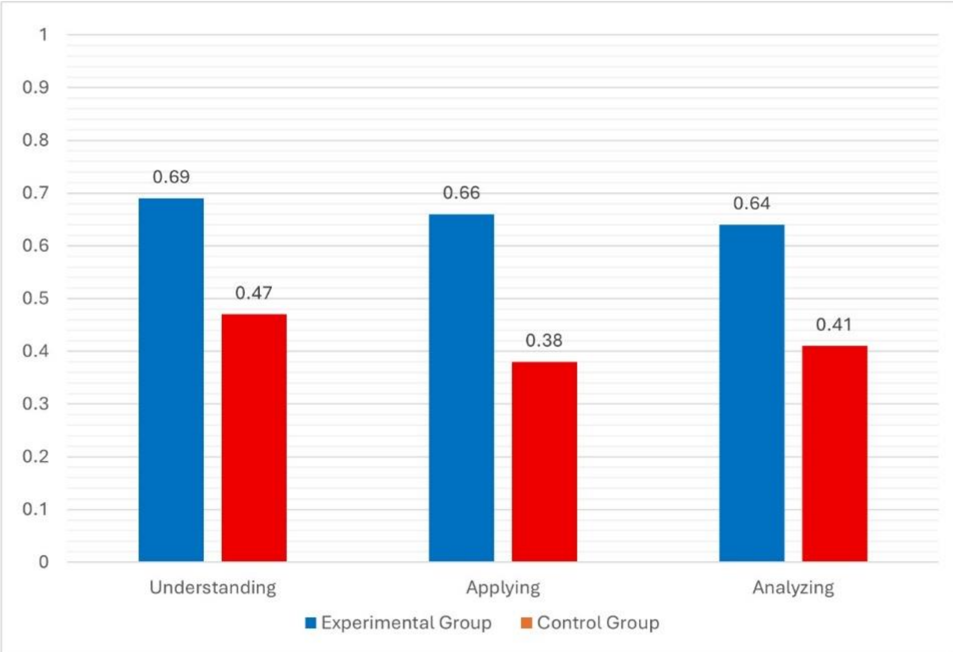

Figure 3. Normalized gain scores by cognitive domain

The analysis of argumentation skills is illustrated in Figure 4. The experimental group, starting from a lower baseline (0.03), achieved a high normalized gain (0.76), whereas the control group recorded a moderate gain (0.66). This demonstrates that the integrated approach was more effective in advancing students' ability to construct and critique scientific arguments. The qualitative classroom observations further supported this finding, revealing that students in the experimental group provided stronger justifications, cited evidence more explicitly, and formulated more coherent rebuttals than their counterparts in the control group.

The observed improvement is consistent with the literature on argumentation-based instruction. Amelia et al. (2021) and Suliyanah et al. (2020) emphasize that robust argumentation requires structured opportunities for students to support or refute claims with logically connected evidence. The enhanced conceptual understanding achieved in the experimental group likely reinforced their ability to produce higher-quality arguments, underscoring the reciprocal relationship between content mastery and reasoning ability.

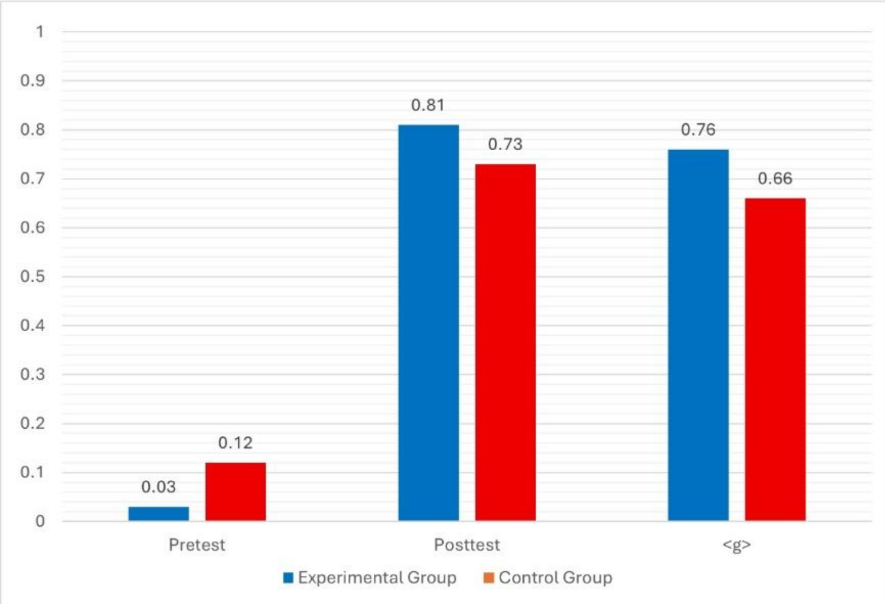

Figure 4. Normalized gain scores for argumentation skills

The present study aimed to determine whether integrating ADI with the scientific method would yield superior learning outcomes compared to ADI alone, and to examine the association between cognitive gains and argumentation gains. The results show clear advantages for the integrated model. Students taught with ADI, combined with the scientific method, achieved higher posttest performance and greater normalized gains in cognitive outcomes than those taught with ADI alone (Figure 2). They also demonstrated substantially stronger improvement in scientific argumentation quality (Figure 4). Taken together, these findings align with and extend prior evidence that ADI supports deep conceptual engagement and argument construction (Amielia et al., 2018; Rosidin et al., 2019; Fakhriyah et al., 2021; Suganda et al., 2023) while the scientific method provides procedural rigor that structures hypothesis generation, experimentation, and inference (Kusumaningrum et al., 2017; Shofiyah et al., 2020; Putra et al., 2020). By combining these complementary strengths within a single instructional sequence, the present work advances the literature that has typically examined these approaches in isolation (Amelia et al., 2021; Satriya & Atun, 2024).

The mechanisms underlying these effects can be interpreted through both cognitive and sociocultural lenses. As outlined in Table 3, the instructional flow anchored each ADI phase to explicit steps of the scientific method and targeted cognitive and argumentation objectives. Framing inquiry around observation, question formulation, hypothesis development, and evidence evaluation cultivated a disciplined, iterative pathway for students to test and refine ideas. Within this structure, ADI's emphasis on discourse required learners to externalize thinking, justify claims, and scrutinize counterarguments, thereby operationalizing Toulmin's (2003) model in classroom practice. From a constructivist perspective, this design created conditions for conceptual change through conflict, explanation, and reconciliation of ideas. At the same time, the coached progression from teacher prompts toward student autonomy is consistent with Vygotskian scaffolding and movement within the ZPD. Such a dual pathway, procedural scaffolding plus dialogic argumentation, helps explain why the integrated condition outperformed ADI alone on both cognitive and epistemic outcomes.

Domain-level analyses further illuminate how the integrated approach shaped learning. The largest gains occurred in Understanding (C2), followed by Applying (C3) and Analyzing (C4) (Figure 3). This profile suggests that the model not only consolidated core conceptual schemas but also facilitated transfer and relational reasoning. These patterns align with findings that argument-based learning deepens conceptual grasp and supports knowledge application when students are required to coordinate data with theory and defend their interpretive choices (Kaçar, 2023). Related studies in physics and chemistry topics have reported similar improvements in reasoning and conceptual performance when argumentation is embedded within inquiry cycles (Inthaud et al., 2019; Kuki et al., 2023), corroborating the present results.

The improvement in argumentation outcomes likewise reflects targeted alignment between activity structure and assessment. Students in the integrated condition progressed from tentative claims to publicly presented and critiqued arguments, and finally to refined conclusions grounded in evidence (Table 3; Figures 3–4). This mirrors Toulmin's (2003) warrant-backing-rebuttal architecture and is consistent with reports that ADI fosters more coherent justifications and explicit use of evidence than conventional teaching (Andriani & Riandi, 2015; Rosidin et al., 2019; Amielia et al., 2018). Prior syntheses and reviews similarly indicate that structured opportunities to argue from data strengthen both the form and substance of students' reasoning (Melta et al., 2024; Misbah et al., 2024; Utami et al., 2024). The present gains therefore reinforce a growing consensus that high-quality argumentation is best cultivated when learners engage in authentic data collection and analysis, followed by critique and revision, rather than through decontextualized exercises (Amelia et al., 2021; Suliyanah et al., 2020).

A central contribution of this study is the observed positive association between cognitive and argumentation gains ($r = 0.61$, $p < 0.001$). This relationship substantiates theoretical claims that content understanding, and argumentation are reciprocally reinforcing: conceptual resources enable more defensible warrants and rebuttals, while the act of constructing and defending arguments consolidates and reorganizes knowledge (Parno et al., 2021; Pan et al., 2021; Pesonen, 2022; Santibáñez, 2024). The present correlation thus provides empirical support for designs that deliberately co-target conceptual and epistemic aims, rather than treating them as separate objectives. In practical terms, the data imply that teachers can leverage argumentation not only to assess understanding but also to cultivate it, provided that argument tasks are situated within genuine inquiry that demands evidence coordination.

At the same time, the study underscores the importance of implementation fidelity. Despite moderate-to-high normalized gains, cognitive improvements did not reach the "high" category, and classroom observations indicated that early sessions under-emphasized questioning and reasoning. Prior work highlights these phases as pivotal for conceptual change because they motivate hypothesis articulation, generate explanatory gaps, and trigger the need for reconciliation (Wieman, 2007; Arini, 2020). The implication is that the benefits of ADI, combined with the scientific method, are contingent on careful orchestration: teachers must allocate sufficient time for student-generated questions, make explicit the criteria for good evidence, and normalize rebuttal as constructive critique. This aligns with recommendations from reviews that stress teacher professional development and task design quality as determinants of ADI effectiveness (Fakhriyah et al., 2021; Suganda et al., 2023).

These findings carry several implications for physics instruction in contexts where laboratory time and inquiry experiences are scarce, as indicated by preliminary observations in the participating schools. First, the integrated model provides a feasible structure for embedding inquiry within limited time frames by coupling essential scientific method steps to ADI discussion routines. Second, the approach appears particularly suited to conceptually challenging topics, such as heat and temperature, where students benefit from alternating between empirical tests and argumentative sense-making. Third, the observed coupling of cognitive and argumentation gains suggests that assessment practices should include both conceptual tests and structured argument tasks to capture the full impact of instruction (Kamaluddin et al., 2023; Sani et al., 2025; Zakirman et al., 2023).

IV. CONCLUSION AND SUGGESTION

The findings of this study demonstrate that integrating the ADI model with the scientific method leads to greater improvements in both cognitive abilities and scientific argumentation skills than using ADI alone in physics instruction. Students in the experimental group achieved higher posttest scores and normalized gains in conceptual understanding across understanding, application, and analysis domains, as well as higher-quality argumentation characterized by stronger justifications, explicit evidence use, and coherent rebuttals. A statistically significant and strong positive correlation between cognitive and argumentation gains further indicates that these competencies are mutually reinforcing, with conceptual mastery supporting more rigorous argument construction and argumentation processes deepening understanding of scientific content.

This study is limited by its relatively small sample size, short intervention duration, and reliance on C2–C4 cognitive measures, which restrict the generalizability of the findings and preclude conclusions about long-term retention or higher-level reasoning. Future research should extend the intervention period, involve larger and more diverse populations, and incorporate broader assessment measures, including synthesis and evaluation levels, performance-based tasks, and qualitative analyses of argumentation processes. The study contributes to the field of physics education by providing empirical evidence for a pedagogical model that simultaneously advances conceptual understanding and epistemic practices. It offers a practical framework for integrating inquiry-based and argumentation-focused instruction, particularly for conceptually challenging topics. It underscores the importance of aligning instructional design with both cognitive and argumentative learning objectives.

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