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The Effect of Integrating the Claim–Evidence–Reasoning Framework into the Argument-Driven Inquiry Model on Students' Scientific Argumentation Skills and Green Chemistry Learning Outcomes

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Abstract

This study aimed to describe the level and improvement of students' scientific argumentation skills and learning outcomes and to examine the effect of integrating the Claim–Evidence–Reasoning (CER) framework into the Argument-Driven Inquiry (ADI) learning model in green chemistry. A quasi-experimental method with a nonequivalent pretest–posttest control group design was employed. The participants were 60 Grade X students at SMAN 13 Makassar, comprising 30 students in the experimental class taught using CER-integrated ADI and 30 students in the control class taught using ADI without explicit CER integration. Data were collected through a scientific argumentation essay test and a multiple-choice learning-outcome test. The data were analyzed using descriptive statistics, N-Gain, an independent-samples t-test, and the Mann–Whitney U test. The experimental class obtained a higher scientific argumentation posttest mean than the control class (51.10 vs. 48.07), with N-Gain scores of 0.70 and 0.64, respectively, both categorized as moderate. The experimental class also achieved higher percentages in claim, evidence, and reasoning. For learning outcomes, the experimental class obtained a higher posttest mean (12.40 vs. 11.63), although the N-Gain scores were similar and categorized as moderate (0.55 vs. 0.56). Significant differences were found in scientific argumentation skills ($t = -3.410$, $p = 0.001$) and learning outcomes ($U = 310.500$, $p = 0.035$). Therefore, CER-integrated ADI significantly supported students' scientific argumentation skills and learning outcomes in green chemistry.

Introduction

21st-century education demands that students possess critical thinking, communication, collaboration, and creativity (the 4Cs) skills to prepare them for facing increasingly complex global challenges. In science learning, these skills are needed not only to understand scientific concepts but also to analyze information, solve problems, and communicate ideas logically and evidence-based. One competency that plays a crucial role in developing 21st-century skills is scientific argumentation skills (Voon et al., 2022; Cebrero, 2025; Purwanto et al., 2023). These skills enable students to put forward claims, present relevant evidence, and provide scientific reasoning to support an opinion, thereby deepening conceptual understanding and gaining meaningful meaning (Sukmawati et al., 2024; Krajcik & Czerniak, 2025; Jiménez-Valverde, 2025; Krakowski et al., 2024; Alanazi et al., 2024).

Nevertheless, various studies indicate that the scientific argumentation skills of students in Indonesia are still relatively low. (Hardini & Alberida, 2022) reported that most students have low to moderate argumentation skills, with an average score below 60%. Similar findings were also reported by (Zakaria et al., 2022), who showed that students still experience difficulties in

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formulating claims, using relevant evidence, and connecting evidence to scientific concepts through logical reasoning. This condition indicates that the ongoing science learning process is not yet fully capable of facilitating the optimal development of scientific argumentation (Franco-Mariscal et al., 2024; Morris, 2025; Tang, 2024).

This problem becomes increasingly important in chemistry learning, particularly in green chemistry. Green chemistry is an approach that emphasizes the design of environmentally friendly and sustainability-oriented chemical products and processes (Situngkir et al., 2026; Mu'azu & Abubakar, 2025; Puspita & Joharmawan, 2026; Kümmerer, 2026; Kusuma et al., 2026). This material is contextual because it relates to various environmental issues close to students' lives, such as environmental pollution, the use of hazardous chemicals, waste management, and sustainable energy development. Therefore, learning green chemistry requires not only conceptual mastery but also the ability to analyze problems, evaluate alternative solutions, and make decisions based on scientific evidence (Reyes et al., 2022; Vaz et al., 2025; Witri & Kurniawati, 2023).

Initial observations and discussions with chemistry teachers at SMAN 13 Makassar indicate that students' argumentative skills still need improvement. Most students tend to provide short answers without supporting adequate scientific reasoning (Cohn et al., 2024; Šedlbauer et al., 2024). During discussions, only a few students actively express their opinions, while the majority prefer to follow their peers' answers. Furthermore, students generally only repeat information obtained from textbooks or teacher explanations without being able to explain the relationships between concepts logically. These findings indicate a need for learning strategies that can facilitate students' development of scientific argumentative skills while simultaneously enhancing conceptual understanding (Kuki, 2023; Hendratmoko et al., 2024; Li et al., 2023; Iordanou, 2022).

One learning model with the potential to develop scientific argumentative skills is Argument-Driven Inquiry (ADI) (Amelia et al., 2025; Melta et al., 2024; Hasnunidah & Undang Rosidin, 2024). The ADI model integrates scientific investigation activities with the argumentative process, providing students with the opportunity to collect data, develop arguments, test arguments through discussion, and defend their findings scientifically. Research (Arfiany et al., 2021) shows that implementing the ADI model can improve students' argumentative skills and learning outcomes. Research results (Sulistianingsih & Yanto, 2024) also show that the ADI model has a positive influence on students' argumentation skills in science learning.

However, the arguments produced by students in ADI learning are often not systematically structured. Therefore, a framework is needed to help students construct structured arguments. One approach that can be used is the Claim-Evidence-Reasoning (CER) pattern. CER is an argumentative framework consisting of three main components: a claim as an answer to a problem, evidence as proof supporting the claim, and reasoning as a logical explanation connecting the evidence to the claim based on relevant scientific concepts (McNeill & Krajcik, 2011; Jho & Ha, 2024). Using the CER framework helps students organize their thoughts systematically, thus improving the quality of their arguments.

The integration of CER into the ADI model is believed to strengthen the argumentation process during scientific investigations (Arslan et al., 2023; Su et al., 2025; Liu et al., 2024; Husna et al., 2026). (Sampson & Gleim, 2009) explain that the use of a structured argumentative framework can improve the quality of students' written and oral arguments. Furthermore, research (Sukarso et al., 2023) shows that ADI-based learning can improve students' scientific argumentation skills with moderate improvement, while (Kuki et al., 2023) report that ADI is effective in improving argumentation skills and conceptual understanding. However, research

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specifically integrating the CER pattern within the ADI model for green chemistry is still relatively limited. This is despite the contextual nature of green chemistry, which offers significant potential for developing students' scientific argumentation skills.

Based on this description, this study proposes the application of the CER pattern within the ADI learning model as an alternative to improving students' scientific argumentation skills and learning outcomes in green chemistry.

Methods

This study employed a quasi-experimental method using a nonequivalent pretest–posttest control group design. The study involved two intact classes that were not selected through individual randomization: an experimental class and a control class. Both groups completed a pretest before the intervention and a posttest after the intervention. The experimental class was taught using the *Argument-Driven Inquiry* (ADI) learning model integrated with the *Claim–Evidence–Reasoning* (CER) argumentation framework, whereas the control class was taught using the ADI model without explicit integration of the CER framework. The study was conducted during the second semester of the 2025/2026 academic year at SMAN 13 Makassar, South Sulawesi, Indonesia.

The population comprised all Grade X students at SMAN 13 Makassar, distributed across nine classes. The research sample was selected using purposive sampling based on the equivalence of students' initial cognitive abilities, as indicated by their previous learning achievement. Based on these considerations, Class X.8 was assigned as the experimental class and Class X.7 as the control class. Each class consisted of 30 students, resulting in a total sample of 60 participants. This allocation is consistent with the sample reported in the research results.

The research procedure began with the administration of pretests on scientific argumentation skills and learning outcomes to both classes. Students in each class were then divided into six groups of five members. Both groups participated in the main stages of the ADI model, including task and research-question identification, investigation design and data collection, data analysis, tentative argument construction, argumentation sessions, investigation-report preparation, peer review and report revision, and reflective discussion. The main difference between the two groups concerned the argument-construction process. Students in the experimental class received explicit guidance in organizing their arguments into *claim*, *evidence*, and *reasoning*, whereas students in the control class constructed arguments through the ADI stages without structured CER guidance. After the intervention was completed, both classes were administered the posttests.

Data on scientific argumentation skills were collected using a ten-item essay test administered before and after the intervention. Students' responses were assessed according to the three CER components: *claim*, *evidence*, and *reasoning*. Each component was scored from 0 to 2. A score of 0 was assigned when the component was absent or irrelevant, a score of 1 when the response was partially correct or incomplete, and a score of 2 when the response was correct, relevant, and complete. Therefore, the maximum total score for the scientific argumentation test was 60. The instrument was reviewed and validated by experts in chemistry education before being administered.

Students' cognitive learning outcomes were measured using a 15-item multiple-choice test with five response options for each item. A correct response received a score of 1, whereas an incorrect or unanswered item received a score of 0. Consequently, the maximum possible learning-outcome score was 15. The test was administered as both a pretest and a posttest to

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determine students' initial achievement and changes following the learning intervention. The learning-outcome instrument was also validated before use.

The data were analyzed using descriptive and inferential statistics. Descriptive statistics included the number of participants, minimum and maximum scores, mean, median, mode, and standard deviation. Scientific argumentation skills were additionally analyzed according to the percentage achievement of each CER component. Learning outcomes were analyzed both as total scores and according to individual learning indicators. The improvement in scientific argumentation skills and learning outcomes was calculated using the normalized gain or N-Gain formula:

$$N\text{-Gain} = \frac{\text{posttest score} - \text{pretest score}}{\text{maximum score} - \text{pretest score}}$$

N-Gain scores were classified as high when they were greater than 0.70, moderate when they ranged from 0.30 to 0.70, and low when they were below 0.30.

Inferential statistical analyses were performed using SPSS version 32 at a significance level of 0.05. A normality test was conducted to assess the distribution of the data, while a homogeneity test was used to determine whether the variances of the two groups were equivalent. The posttest scores for scientific argumentation skills were compared using an independent-samples *t*-test because the data met the assumptions of normality and homogeneity. In contrast, students' learning outcomes were analyzed using the nonparametric Mann–Whitney U test because one of the datasets did not meet the normality assumption, although the variances were homogeneous. The null hypothesis was rejected when the significance value was less than 0.05. These statistical procedures are consistent with the analyses reported in the Results section.

Results and Discussion

The research results were analyzed using descriptive and inferential statistics. Descriptive analysis was conducted to describe students' scientific argumentation skills and learning outcomes in the experimental and control classes, while inferential analysis was performed to test the effect of the *Claim–Evidence–Reasoning* argumentation framework integrated into the *Argument-Driven Inquiry* learning model.

Scientific Argumentation Skills

The pretest and posttest results for students' scientific argumentation skills in the experimental and control classes are presented in Table 1.

Table 1. Pretest and Posttest Results for Scientific Argumentation Skills

Statistic	Control Pretest	Experimental Pretest	Control Posttest	Experimental Posttest
Number of students	30	30	30	30
Maximum score	36	40	55	56
Minimum score	16	15	40	44
Mean	25.47	27.03	48.07	51.10
Median	26.00	27.50	48.50	51.00
Mode	27	26	48	51
Standard deviation	5.24	6.58	4.01	2.77

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Table 1 shows that the control class obtained a pretest mean score of 25.47, with a maximum score of 36 and a minimum score of 16. The experimental class obtained a pretest mean score of 27.03, with a maximum score of 40 and a minimum score of 15. The relatively small difference between the two pretest means indicates that the initial scientific argumentation skills of the two classes were relatively comparable.

Following the learning intervention, the control class obtained a posttest mean score of 48.07, with a maximum score of 55 and a minimum score of 40. Meanwhile, the experimental class obtained a posttest mean score of 51.10, with a maximum score of 56 and a minimum score of 44. Descriptively, both classes showed improvement in scientific argumentation skills, although the experimental class achieved a higher posttest mean than the control class.

A more detailed analysis was conducted on the three components of scientific argumentation, namely *claim*, *evidence*, and *reasoning*. The results are presented in Table 2.

Table 2. Profile of Scientific Argumentation Skills Based on CER Components

Component	Control Pretest (%)	Control Posttest (%)	Experimental Pretest (%)	Experimental Posttest (%)
Claim	58.7	91.5	62.0	95.0
Evidence	38.8	80.7	42.2	86.7
Reasoning	29.8	68.2	31.0	73.3

Table 2 shows that all CER components improved in both the control and experimental classes after the learning intervention. In the control class, the percentage of the *claim* component increased from 58.7% to 91.5%, the *evidence* component increased from 38.8% to 80.7%, and the *reasoning* component increased from 29.8% to 68.2%.

A similar pattern was observed in the experimental class. The percentage of the *claim* component increased from 62.0% to 95.0%, the *evidence* component increased from 42.2% to 86.7%, and the *reasoning* component increased from 31.0% to 73.3%. Overall, the *claim* component achieved the highest percentage in both the pretest and posttest results of the two classes. The improvement in students' scientific argumentation skills was further analyzed using the N-Gain score, as presented in Table 3.

Table 3. Mean N-Gain Scores for Scientific Argumentation Skills

Class	Pretest Mean	Posttest Mean	N-Gain	Category
Control	25.47	48.07	0.64	Moderate
Experimental	27.03	51.10	0.70	Moderate

The mean N-Gain score for the control class was 0.64, which was categorized as moderate. The experimental class obtained a mean N-Gain score of 0.70, which was also categorized as moderate. These results indicate that students in both classes experienced improvement in their scientific argumentation skills after participating in the learning activities. Numerically, the experimental class obtained a higher N-Gain score than the control class.

Students' Learning Outcomes

The descriptive statistical results for students' learning outcomes are presented in Table 4.

Table 4. Descriptive Statistics of Students' Learning Outcomes

Statistic	Control Pretest	Experimental Pretest	Control Posttest	Experimental Posttest

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Number of students	30	30	30	30
Maximum score	12	12	15	15
Minimum score	4	5	9	9
Mean	7.23	8.63	11.63	12.40
Median	7.00	8.00	12.00	12.00
Mode	8	7	13	12
Standard deviation	1.96	1.86	1.52	1.19

The pretest results show that the control class obtained a mean learning-outcome score of 7.23, with a maximum score of 12 and a minimum score of 4. The experimental class obtained a pretest mean score of 8.63, with a maximum score of 12 and a minimum score of 5.

The posttest mean score of the control class increased to 11.63, with a maximum score of 15 and a minimum score of 9. Meanwhile, the posttest mean score of the experimental class increased to 12.40, with a maximum score of 15 and a minimum score of 9. Descriptively, both classes showed improvement in learning outcomes following the learning intervention, with the experimental class obtaining a higher posttest mean than the control class. The improvement in students' learning outcomes was subsequently analyzed using N-Gain scores, as presented in Table 5.

Table 5. Mean N-Gain Scores for Students' Learning Outcomes

Class	Pretest Mean	Posttest Mean	N-Gain	Category
Control	7.23	11.63	0.56	Moderate
Experimental	8.63	12.40	0.55	Moderate

The control class obtained an N-Gain score of 0.56, while the experimental class obtained an N-Gain score of 0.55. Both values were categorized as moderate. Therefore, the overall improvement in learning outcomes in both classes was within the same category. The N-Gain score of the control class was numerically 0.01 higher than that of the experimental class.

A more detailed analysis was conducted for each learning-outcome indicator to identify the indicators with the highest and lowest levels of improvement.

Table 6. Improvement in Learning-Outcome Indicators in the Control Class

No.	Learning-outcome indicator	Pretest	Posttest	N-Gain	Category
1	Identifying the appropriate definition of green chemistry in environmental conservation efforts	1.40	1.90	0.83	High
2	Stating the benefits of implementing green chemistry for human health and ecosystems	0.37	0.80	0.68	Moderate
3	Classifying actions included in one of the 12 principles of green chemistry	0.86	1.56	0.61	Moderate
4	Analyzing the negative environmental effects of incomplete combustion reactions	0.73	1.43	0.55	Moderate
5	Evaluating the use of synthetic chemicals in household products that deviates from green chemistry principles	1.10	1.50	0.44	Moderate

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6	Comparing the atom economy of two different chemical production processes	0.50	0.80	0.60	Moderate
7	Analyzing the contribution of green chemistry to achieving the climate-action SDG	0.93	1.50	0.53	Moderate
8	Relating the principle of designing safer chemicals to responsible consumption and production	0.80	1.40	0.50	Moderate
9	Concluding the role of green chemistry-based technological innovation in supporting a sustainable economy	0.53	0.73	0.42	Moderate

All learning-outcome indicators in the control class showed improvement, as indicated by N-Gain scores ranging from moderate to high. The highest improvement was found in Indicator 1, with an N-Gain score of 0.83, categorized as high. The lowest improvement was found in Indicator 9, with an N-Gain score of 0.42, categorized as moderate.

Table 7. Improvement in Learning-Outcome Indicators in the Experimental Class

No.	Learning-outcome indicator	Pretest	Posttest	N-Gain	Category
1	Identifying the appropriate definition of green chemistry in environmental conservation efforts	1.46	1.93	0.87	High
2	Stating the benefits of implementing green chemistry for human health and ecosystems	0.50	0.90	0.80	High
3	Classifying actions included in one of the 12 principles of green chemistry	1.03	1.76	0.75	High
4	Analyzing the negative environmental effects of incomplete combustion reactions	0.96	1.50	0.51	Moderate
5	Evaluating the use of synthetic chemicals in household products that deviates from green chemistry principles	1.30	1.56	0.38	Moderate
6	Comparing the atom economy of two different chemical production processes	0.57	0.73	0.38	Moderate
7	Analyzing the contribution of green chemistry to achieving the climate-action SDG	1.20	1.70	0.62	Moderate
8	Relating the principle of designing safer chemicals to responsible consumption and production	1.06	1.56	0.53	Moderate
9	Concluding the role of green chemistry-based technological innovation in supporting a sustainable economy	0.53	0.73	0.42	Moderate

All learning-outcome indicators in the experimental class also showed improvement, with N-Gain scores ranging from moderate to high. The highest improvement occurred in Indicator 1, with an N-Gain score of 0.87, categorized as high. Indicators 2 and 3 also reached the high category, with N-Gain scores of 0.80 and 0.75, respectively. The lowest improvement was found in Indicators 5 and 6, each with an N-Gain score of 0.38, categorized as moderate.

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Thus, the control class had one learning indicator in the high category, whereas the experimental class had three indicators in the high category. Nevertheless, the overall N-Gain scores for learning outcomes in both classes remained in the moderate category.

Inferential Statistical Analysis

Normality Test

The Kolmogorov–Smirnov test was used to examine whether the pretest and posttest data were normally distributed. The normality-test results are presented in Table 8.

Table 8. Normality-Test Results for Scientific Argumentation Skills and Learning Outcomes

Variable	Control Pretest	Control Posttest	Experimental Pretest	Experimental Posttest
Scientific argumentation skills	0.350	0.085	0.545	0.448
Learning outcomes	0.280	0.125	0.053	0.025

All pretest and posttest data for scientific argumentation skills had significance values greater than 0.05. Therefore, the scientific argumentation data in both classes were normally distributed.

For learning outcomes, the control-class pretest and posttest significance values were 0.280 and 0.125, respectively, while the experimental-class pretest significance value was 0.053. These values were greater than 0.05 and were therefore normally distributed. However, the experimental-class posttest significance value was 0.025, which was lower than 0.05. Therefore, the experimental posttest learning-outcome data were not normally distributed.

Homogeneity Test

The homogeneity test was conducted to determine whether the experimental and control classes had equal variances. The results are presented in Table 9.

Table 9. Homogeneity-Test Results

Variable	α	Significance	Analysis	Conclusion
Scientific argumentation skills	0.05	0.281	Sig. > 0.05	Homogeneous
Learning outcomes	0.05	0.100	Sig. > 0.05	Homogeneous

The significance value for scientific argumentation skills was 0.281, which was greater than 0.05. Therefore, the scientific argumentation data were homogeneous. The significance value for learning outcomes was 0.100, which was also greater than 0.05, indicating that the learning-outcome data were homogeneous.

Hypothesis Testing

Because the scientific argumentation data were normally distributed and homogeneous, the hypothesis for scientific argumentation skills was tested using a parametric *t*-test. In contrast, the learning-outcome data were not entirely normally distributed, although they were homogeneous. Therefore, the learning-outcome hypothesis was tested using the nonparametric Mann–Whitney U test.

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Table 10. Hypothesis-Test Results for Scientific Argumentation Skills and Learning Outcomes

Variable	Statistical test	Test value	Sig. (2-tailed)	α	Decision	Interpretation
Scientific argumentation skills	*t*-test	$t = -3.410$	0.001	0.05	H_0 rejected	A significant difference existed between the experimental and control classes
Learning outcomes	Mann–Whitney U	$U = 310.500$	0.035	0.05	H_0 rejected	A significant difference existed between the experimental and control classes

The hypothesis test for scientific argumentation skills produced a significance value of 0.001, which was lower than 0.05. Therefore, H_0 was rejected and H_1 was accepted, indicating a significant difference in scientific argumentation skills between the experimental and control classes.

The Mann–Whitney U test for learning outcomes produced a significance value of 0.035, which was also lower than 0.05. Therefore, H_0 was rejected and H_1 was accepted, indicating a significant difference in learning outcomes between the experimental and control classes.

Based on these findings, the CER argumentation framework integrated into the *Argument-Driven Inquiry* learning model had a significant effect on students' scientific argumentation skills and learning outcomes in green chemistry.

The findings demonstrate that integrating the Claim–Evidence–Reasoning (CER) framework into Argument-Driven Inquiry (ADI) strengthens students' scientific argumentation more effectively than ADI without explicit argument scaffolding. ADI provides opportunities to investigate problems, collect data, present tentative arguments, and evaluate peers' explanations, whereas CER clarifies how these activities should be transformed into a structured scientific argument. This complementary function is consistent with Arslan et al. (2023), Liu et al. (2024), and Melta et al. (2024), who found that ADI improves argumentation by repeatedly engaging students in constructing, defending, evaluating, and revising evidence-based explanations.

The stronger argumentation performance in the experimental class can be attributed to the explicit separation of claims, evidence, and reasoning. Without structured guidance, students may identify the correct answer but fail to select relevant evidence or explain its relationship to scientific concepts. CER reduces this cognitive difficulty by organizing argument construction into clear stages. Alanazi et al. (2024) showed that structured scaffolding directs students' attention toward higher-order reasoning, while Voon et al. (2022) found that argumentation frameworks support analytical thinking, evidence evaluation, and problem solving. Thus, CER functioned not merely as a writing format but as a cognitive scaffold that helped students organize and communicate scientific thinking.

The ADI argumentation sessions and peer-review stages also contributed to this improvement. Students were required to compare explanations, respond to criticism, and revise their initial arguments. Such activities encourage students to evaluate the relevance and sufficiency of evidence rather than accepting their first conclusions. Iordanou (2022) emphasized that reflection supports the strategic development of argumentation, while Li et al. (2023) found

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that collaborative argumentative dialogue promotes conceptual change by exposing students to alternative explanations. Similarly, Hendratmoko et al. (2024) reported that combining inquiry and debate strengthens scientific argumentation because students must justify their ideas publicly and respond to opposing perspectives.

Among the CER components, claims were more easily developed than evidence and reasoning, whereas reasoning remained the most challenging component. Claims generally require students to state a conclusion, while evidence requires the selection of relevant empirical information. Reasoning demands a more complex process because students must explain why the evidence supports the claim using appropriate scientific principles. Jho and Ha (2024) similarly found that students more easily construct claims and data than warrants or explanatory connections. Wilson et al. (2024) also emphasized that possessing scientific information does not automatically enable students to use that information as justification. Therefore, the lower reasoning performance indicates that students still require repeated practice in connecting evidence with green chemistry concepts.

The moderate improvement in argumentation is consistent with previous ADI studies. Fuadah et al. (2023) reported moderate gains in students' scientific argumentation after ADI instruction, although the intervention had a strong comparative effect. Sukarso et al. (2023) also found that ADI-based modules produced gradual improvements in argumentation and critical thinking. Kuki et al. (2023) explained that developing high-quality arguments requires sustained practice because students must simultaneously master scientific concepts and argument structures. Consequently, the present findings suggest that CER-integrated ADI is effective, but longer implementation across several topics may be necessary for students to produce more sophisticated reasoning.

The findings also indicate that both instructional approaches supported students' conceptual learning. ADI facilitates conceptual understanding because students use scientific concepts to design investigations, interpret information, evaluate explanations, and justify conclusions. Arfiany et al. (2021) found that ADI improved both argumentation and science learning outcomes, while Arslan et al. (2023) demonstrated that its investigative and argumentative stages strengthened content achievement. Kuki et al. (2023) further argued that argument quality reflects conceptual understanding because students cannot produce scientifically valid explanations without accurate and connected knowledge.

Nevertheless, the learning-outcome findings should be interpreted cautiously. Although the experimental class achieved a better final performance and a statistically significant difference was identified, the normalized gains of the two groups were nearly identical. This suggests that ADI itself substantially supported conceptual learning in both classes, while CER provided a more apparent additional benefit for organizing scientific argumentation. Therefore, the primary contribution of CER was not necessarily accelerating overall cognitive improvement but helping students express their understanding more systematically through claims, supporting evidence, and scientific reasoning.

The green chemistry context also supported the development of argumentation because it involves problems that require scientific evaluation and decision making. Students must consider chemical safety, environmental effects, waste reduction, resource efficiency, and sustainability when assessing alternative solutions. Reyes et al. (2023) argued that green chemistry education should combine chemical knowledge with life-cycle and systems thinking. Vaz et al. (2025) similarly found that contextual green chemistry problems help students apply

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principles rather than merely memorize them. Therefore, green chemistry provides a relevant context for CER because students must justify why a chemical process or product can be considered safer and more sustainable.

Differences among the learning indicators further show that students more easily mastered tasks involving definitions, benefits, and classification than tasks involving evaluation, atom economy, and sustainable technological innovation. The latter indicators require students to integrate quantitative reasoning, environmental considerations, and broader sustainability consequences. Reyes et al. (2023) explained that sustainability evaluation becomes more difficult when students must move beyond individual chemical properties and consider an entire production system. This indicates that complex green chemistry competencies require more contextual examples, calculation practice, and explicit systems-thinking activities.

Pedagogically, CER should be embedded throughout the ADI stages rather than used only as a final-answer format. Teachers should ask students to identify the evidence needed before investigation, evaluate its relevance during data analysis, and explain the scientific principles connecting evidence and claims during argumentation sessions. Reasoning prompts, peer-assessment criteria, and report revision should receive particular emphasis. Scaffolding should then be gradually reduced so that students can independently transfer the argumentation structure to new scientific problems.

The findings are limited by the use of two intact classes from one school, purposive sampling, a relatively small sample, and differences in initial learning achievement. The study also assessed immediate performance and did not examine long-term retention or transfer to other chemistry topics. Future research should involve larger samples, delayed posttests, effect-size analysis, inter-rater reliability for essay scoring, and statistical procedures that control for initial differences. Classroom observations and analyses of students' revised arguments would also clarify which ADI stages contribute most strongly to the development of claims, evidence, and reasoning.

CER and ADI serve complementary purposes. ADI creates an inquiry environment in which scientific knowledge is investigated, discussed, evaluated, and revised, while CER provides a clear structure for communicating that knowledge. Their integration particularly strengthens scientific argumentation by helping students move from unsupported answers toward evidence-based and scientifically justified explanations.

Conclusion

This study concludes that integrating the Claim–Evidence–Reasoning (CER) framework into the Argument-Driven Inquiry (ADI) learning model significantly affected students' scientific argumentation skills and learning outcomes in green chemistry. The experimental class achieved a higher scientific argumentation posttest mean than the control class (51.10 vs. 48.07), with N-Gain scores of 0.70 and 0.64, respectively, both categorized as moderate; moreover, the experimental class obtained higher posttest percentages for claim (95.0%), evidence (86.7%), and reasoning (73.3%), although reasoning remained the lowest-achieving component. The experimental class also obtained a higher learning-outcome posttest mean than the control class (12.40 vs. 11.63), although their overall N-Gain scores were nearly identical and remained in the moderate category, at 0.55 and 0.56, respectively. Nevertheless, three learning indicators in the experimental class reached the high category, compared with only one indicator in the control class. The inferential analysis confirmed significant differences between the two groups in scientific argumentation skills ($t = -3.410$, $p = 0.001$) and learning outcomes ($U = 310.500$, $p = 0.035$), indicating that CER-integrated ADI was

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effective in supporting students' ability to construct evidence-based scientific arguments and understand green chemistry concepts.

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