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Fostering Students' Critical Thinking through ADI-SSI Learning Model: A Study in Plant Physiology Learning

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Abstract

The Fourth Industrial Revolution has increased the demand for higher education institutions to develop students who not only possess strong disciplinary comprehension but also demonstrate well-developed critical thinking skills. However, observations of Biology Education students indicated that their critical thinking skills remain inadequate, particularly in relating plant physiology concepts to social and environmental issues. The study purpose is to examine the efficiency of an Argument-Driven Inquiry model integrated with Socio-Scientific Issues (ADI-SSI) in enhancing students' critical thinking skills in a Plant Physiology course. This paper employed a quasi-experimental design involving nonequivalent experimental groups with pretest and posttest measurements. The participants were Biology Education students at a public university in Bengkulu Province, Indonesia, selected through purposive sampling. Students' critical thinking skills were assessed using an essay-based test developed according to the FRISCO framework (focus, reason, inference, situation, clarity, and overview). Data were analyzed using ANCOVA Quade's Rank test, and the magnitude of influence was analyzed using effect size for the F (Eta Squared) test. The results revealed a statistically significant difference in students' critical thinking skills between the experimental and control groups. [$F(1,68) = 76.332$, $p < 0.001$], with a great effect size ($\eta^2 = 0.53$). The greatest improvements were observed in the focus, situation, clarity, and overview dimensions. These findings indicate that integrating scientific inquiry with socio-scientific issues encourages students to think logically, evaluate evidence objectively, and consider social and ethical dimensions when constructing scientific arguments. The ADI-SSI model proved effective in improving students' critical thinking skills while strengthening the relevance of biology learning to contemporary global challenges.

Keywords: argument driven inquiry (ADI), critical thinking skills, plant physiology course, socio-scientific issues (SSI)

INTRODUCTION

As the world enters the era of Industry 4.0, higher education is supposed to produce graduates who acquire not only disciplinary knowledge but also higher-order thinking skills, particularly critical thinking (Ardias et al., 2026; Bezanilla et al., 2021). This competency is especially essential for pre-service biology teachers, as they will be required to navigate rapid advances in science and technology while coping with complex problems such as climate change, biodiversity loss, the use of transgenic products, and food security (Yennita et al., 2024). Consequently, the role of educators broadens beyond delivering subject matter in the classroom. They are also expected to help students develop the ability to analyze information, evaluate issues from multiple viewpoints, and make well-reasoned conclusions based on sound evidence (Astutik et al., 2025; Herlinawati et al., 2024). To fulfill this responsibility effectively, pre-service biology teachers must possess strong critical thinking skills, enabling them to teach biological concepts as well as to guide students in understanding and responding to the diverse challenges they encounter in everyday life (Maryuningsih et al., 2020).

However, observations conducted during the Plant Physiology course revealed that students' critical thinking skills remain inadequate. Most students still relied heavily on memorizing concepts and theories (82%), rarely asked questions that could stimulate deeper discussion (76%), and had difficulty evaluating information and relating it to issues encountered in society (58%). These findings suggest that classroom instruction continues to emphasize content delivery rather than providing students with opportunities to process, question, and apply what they have learned. As a result, many students have not yet developed a comprehensive understanding of plant physiology and continue to struggle when asked to connect biological concepts with authentic, real-world contexts. This evidence highlights the need to strengthen students' critical thinking skills so that they are better prepared to fulfill their future roles as biology educators who can effectively link scientific concepts to real-life challenges (Chen et al., 2026; Zulfadli et al., 2025).

The limited improvement of critical thinking skills affects students' learning processes. Additionally, it also undermines their readiness to become future biology educators (Islamiyati et al., 2023; Iwan et al., 2023). Learners who are not accustomed to thinking critically are more likely to struggle to evaluate the credibility of information, construct arguments grounded in scientific evidence, and explain biological issues from a comprehensive perspective (Ariadila et al., 2023; Astutik et al., 2025). Within the framework of the Plant Physiology course, this limitation often leads students to perceive the subject as a collection of isolated concepts rather than as knowledge that can be applied to address societal challenges, such as environmental pollution, food insecurity, and climate change (Fatmawati et al., 2024; Yennita et al., 2025). If this situation persists, graduates may be insufficiently prepared to design and implement biology instruction that fosters students' critical thinking in addressing the complex challenges they encounter in their everyday lives (Astutik et al., 2025; Maryuningsih et al., 2020).

Critical thinking skills do not develop on their own; rather, they must be cultivated through learning experiences that provide learners with opportunities to observe phenomena, examine evidence, construct arguments, and defend their viewpoints with well-justified reasoning. Moreover, learning in higher education should be planned not only to help students acquire conceptual understanding but also to empower them to implement that knowledge in addressing problems. One instructional approach that aligns well with this objective is the Argument-Driven Inquiry (ADI) model, as it places scientific inquiry and evidence-based discussion at the core of the learning process (Fakhriyah et al., 2021; Grooms et al., 2015).

Scientific inquiry becomes more meaningful when it is grounded in issues that genuinely affect society. For this reason, the Argument-Driven Inquiry (ADI) model can be integrated with the Socio-Scientific Issues (SSI) approach, which uses authentic societal issues as the context for learning. Through this approach, students develop comprehension of plant physiology concepts and learn to examine complex issues from scientific, social, and ethical perspectives before drawing conclusions

or making informed decisions (Nolan & Zeidler, 2025; Sadler et al., 2016; Zeidler & Nichols, 2009). Consequently, learning extends beyond conceptual understanding by equipping learners to implement their biological knowledge to interpret and respond to real-world challenges.
Previous studies have demonstrated that the Argument-Driven Inquiry (ADI) model enhances the quality of study by encouraging students to engage more actively in scientific inquiry (Arslan et al., 2023), develop a further understanding of scientific concepts (Tukiran et al., 2019), and construct as well as defend arguments supported by scientific evidence (Fuadah et al., 2023; Satriya & Atun, 2024). However, most of these studies have focused primarily on laboratory-based activities, providing limited opportunities for learners to associate their scientific investigations with the societal issues they encounter in everyday life. In contrast, the Socio-Scientific Issues (SSI) approach introduces authentic problems, such as climate change and food security, as learning contexts that encourage students to examine problems from scientific, social, and ethical perspectives (Genisa et al., 2020). Nevertheless, SSI-based instruction generally lacks a structured scientific inquiry process (Arifin, Sukarmin, & Saputro, 2025; Chowdhury et al., 2020; Dusturi et al., 2024), limiting students' opportunities to develop evidence-based argumentation. Therefore, integrating the ADI model with the SSI approach (ADI–SSI) holds considerable promise for fostering learners' critical thinking skills more comprehensively. While ADI provides a systematic framework for scientific inquiry and evidence-based argumentation, SSI situates learning within authentic societal issues that are relevant to students' everyday lives.

Based on this rationale, incorporating the Argument-Driven Inquiry (ADI) model with the Socio-Scientific Issues (SSI) approach (ADI–SSI) represents a highly relevant instructional strategy for fostering the critical thinking skills of pre-service biology teachers. Despite its theoretical potential, empirical evidence regarding the effectiveness of ADI–SSI integration in Plant Physiology courses at the higher education level remains limited. Therefore, this study aims to examine the extent to which the ADI–SSI model enhances students' critical thinking skills in a Plant Physiology course. The findings are required to assist in the advancement of science education by contributing empirical evidence for the implementation of innovative instructional approaches in higher education and by supporting the preparation of future biology educators who are critical thinkers, reflective practitioners, and adaptive to the challenges of the twenty-first century.

RESEARCH METHOD

Research Design

This study employed a quasi-experimental research design using a nonequivalent pre-test and post-test control group design (Creswell, 2012; Leedy & Ormrod, 2021). The study objective is to examine the effect of the ADI-SSI instructional model on the critical thinking skills of undergraduate students registered in the Biology Education Study Program in the Plant Physiology course. The experimental group received the ADI-SSI model treatment; in contrast, the control group was taught using the direct instruction model. The critical thinking skills of students in both groups were assessed using pre-tests and post-tests, and the findings were subsequently compared to establish the effect of the instructional treatment. The study's design is presented in Table 1.

Table 1. Research Design

Class	Pre-test	Treatment	Post-test
Control	X1	P1	Y1
Experiment	X2	P2	Y2

Description:
P1 = Treatment in the control class (Direct instruction)
P2 = Treatment in the experimental class (ADI-SSI)
X1 = Pre-test control class
X2 = Pre-test experimental class
Y1 = Post-test control class
Y2 = Post-test experimental class

Population and Samples

The population of the study is the undergraduate students registered in the Biology Education Program at a public university in Bengkulu Province in the 2024/2025 academic year. 104 students are the population, distributed across three classes. The sample selection used purposive sampling based on several criteria: (1) enrollment in and attendance of the plant physiology course; (2) membership in a class with a normally distributed score distribution; and (3) membership in a class with homogeneous variance. The normality and homogeneity criteria were established based on an analysis of students' prior learning achievement scores using the Shapiro–Wilk test and Levene's test. Among the classes that met all three criteria, two classes were selected as the research sample, with one designated as the experimental group and the other as the control group.

Research Procedures

The study was conducted through a series of interconnected stages. It began with a preliminary observation to identify the existing instructional conditions, students' competency achievement, and the learning challenges that served as the basis for formulating the research objectives. Subsequently, a literature review was conducted, followed by the development of the critical thinking assessment instrument, the preparation of instructional materials, and the selection of the research sample.

The main phase of the study involved a quasi-experimental implementation in the Plant Physiology course over eight weeks. The instructional intervention consisted of eight class meetings organized into four ADI-SSI learning cycles, with each cycle spanning two meetings. The four learning cycles focused on transpiration, plant nutrition, photosynthesis, and plant responses to environmental stress. Before the intervention began, students in both groups completed a pre-test to assess their initial critical thinking skills.

The control group received instruction through the direct instruction model combined with assignment-based learning. In contrast, the experimental group was taught using the ADI-SSI model, which comprises seven instructional phases (Walker et al., 2011): (1) classifying the assignment, formulating the research question, and developing the investigation method; (2) collecting and identifying data; (3) constructing a conditional argument; (4) conducting an argumentation session; (5) preparing an analysis report; (6) engaging in double-blind group peer review; and (7) revising the analysis report.

During each learning cycle, learners examined a socio-scientific issue connected to the corresponding Plant Physiology subject as the learning context. They then formulated research questions, designed and conducted analysis or laboratory activities, collected and analyzed data, constructed evidence-based arguments, defended their arguments through scientific discussion, conducted peer reviews of other groups' reports, and revised their analysis reports based on the feedback received. Accordingly, each learning cycle integrated scientific inquiry, evidence-based argumentation, and reflective learning through peer review within the context of socio-scientific issues.

Following the completion of the instructional intervention, learners in both groups completed a post-test to measure their critical thinking skills. The collected data were subsequently analyzed to address the research objectives.

Data Collection and Research Instrument

The study's data collection consisted of students' critical thinking skills scores obtained from the pre-test and post-test of the instructional intervention in both the control and experimental groups. Critical thinking skills were assessed by a 12-item essay examination. The instrument was improved based on the critical thinking elements proposed by Ennis (2011), commonly referred to by the acronym FRISCO, which comprises six elements: (1) *focus*; (2) *reason*; (3) *inference*; (4) *situation*; (5) *clarity*; and (6) *overview*. Before being employed in the study, the instrument underwent validity and reliability testing. The results indicated that all test items met the validity criterion based on the Pearson product–moment correlation analysis ($p < 0.01$) (Kurtz & Mayo, 1979; Metsämuuronen, 2022). The reliability test, using Cronbach's alpha, yielded a coefficient of 0.71, indicating that the instrument demonstrated good reliability (Dorsah, 2026; Tavakol & Dennick, 2011).

Data Analysis Techniques

Learners' critical thinking scores were evaluated using the nonparametric Quade's Rank Analysis of Covariance in SPSS Statistics version 27. This nonparametric procedure was chosen because the data violated one of the assumptions required for the parametric analysis of one-way ANCOVA, namely, the normality of the residuals [$W(70) = 0.764$, $p < 0.001$] (Strunk & Mwavita, 2024). The magnitude of the instructional model's effect on learners' critical thinking skills was subsequently determined by calculating the effect size (eta squared, η^2). The effect size values were explicated according to the criteria proposed by Becker (2000) and Ellis (2010) as presented in Table 2.

Table 2. Criteria for Effect Size for F Test

Effect Size	Eta Squared Value
Low	0.01
Medium	0.06
High	0.14

RESULT AND DISCUSSION

Result

The pre-test and post-test result scores of critical thinking skills of students in the control class and experimental class are presented in Table 3.

Table 3. Students' Critical Thinking Skills Scores in Plant Physiology Course

No	Description	Control Class		Experimental Class	
		Pre-test	Post-test	Pre-test	Post-test
1	Sample	34	34	36	36
2	Mean	35.56	70.06	37.72	80.05
3	Standard Deviation	8.85	10.13	8.73	7.20
4	Minimum	14.00	42.00	22.00	67.00
5	Maximum	53.00	89.00	56.00	97.00

As depicted in Table 3, the control group consisted of 34 students; conversely, the experimental group included 36 students. The mean pre-test score was 35.56 for the control group and 37.72 for the experimental group. Following the instructional intervention, the mean post-test scores increased to 70.06 and 80.05 for the control and experimental groups, respectively. The distribution of students' critical thinking scores in both groups is presented in Figures 2 and 3.

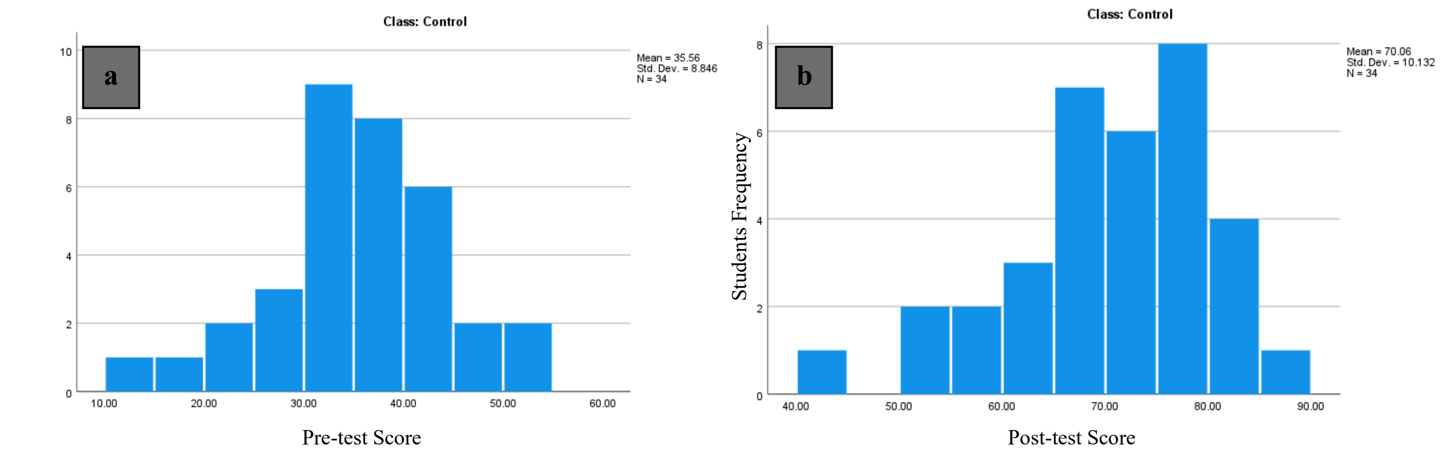

Figure 1. Distribution of pre-test (a) and post-test (b) scores of students' critical thinking skills in the control class

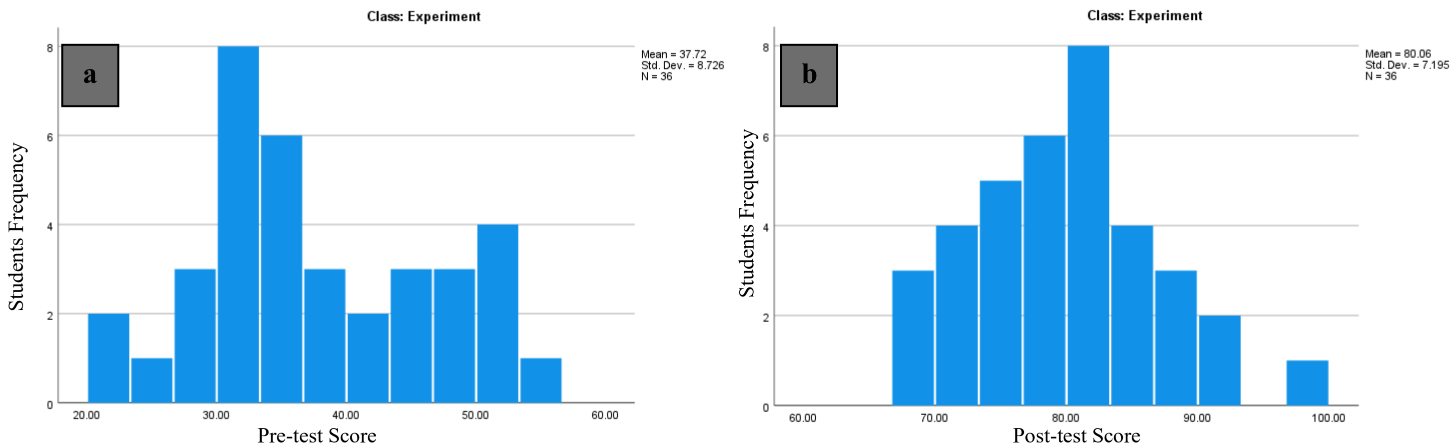

Figure 2. Distribution of pre-test (a) and post-test (b) scores of students' critical thinking skills in the experimental class

The students' critical thinking data did not meet the parametric statistical assumptions required for the one-way ANCOVA test. Specifically, the residuals data were not normally distributed [W(70) = 0.764, *P* = < 0.001]. Hence, the data were analyzed using the nonparametric Quade's Rank Analysis of Covariance in SPSS version 27. The findings of the analysis are presented in Table 4.

Table 4. Quade's Rank of Covariance Analysis Results

Unstandardized Residual							
	Sum of Squares	**Df**	**Mean Square**	**F**	**Sig.**	**Eta Squared**	**Information**
Between Groups	5436.525	1	5436.525	76.332	<0.001	0.53	High Influence
Within Groups	4843.105	68	71.222				
Total	10279.630	69					

The results presented in Table 4 indicate important dissimilarities in students' critical thinking skills between the experimental and control groups after controlling for their initial critical thinking skills [F(1,68) = 76.332, p < 0.001, ?^{2} = 0.53]. These findings suggest that implementing the Argument-Driven Inquiry integrated with Socio-Scientific Issues (ADI-SSI) model had a substantial effect on improving students' critical thinking skills, as reflected by the large effect size (η^2 = 0.53). A comparison of students' critical thinking performance through each indicator between the experimental and control groups is presented in Figure 3.

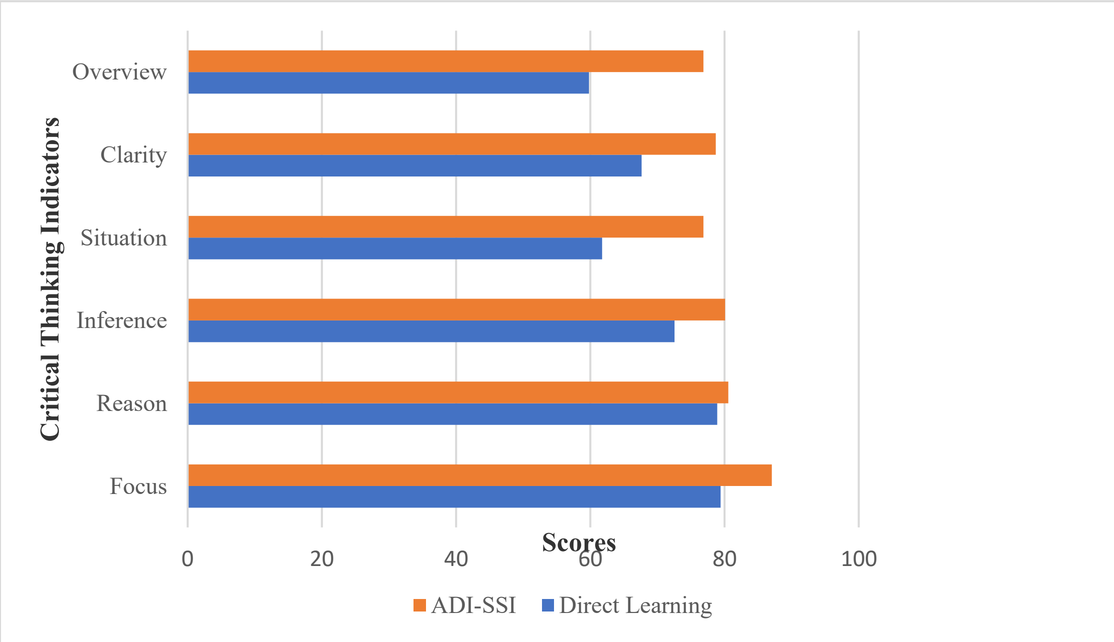

Figure 3. Critical thinking skills achievement for each indicator in the control and experimental class.

Figure 3 shows a comparison of critical thinking skills achieved by students in the control class and the experimental class. The analysis covers six indicators of critical thinking skills, namely (1) focus, (2) reasoning, (3) inference, (4) situation, (5) clarity, and (6) overview. In general, the ADI-SSI model shows consistently higher results on all indicators compared to direct learning. The most notable improvement was seen in the indicators of focus, situation, clarity, and overview, indicating that the application of the ADI-SSI model was more effective in training students to focus their attention on problems, use relevant information, provide easy-to-understand explanations, and thoroughly examine and review the results of problem solving from start to finish.

Discussion

Higher education is increasingly oriented toward developing advanced cognitive skills, such as critical thinking, as a key component of Outcome-Based Education (OBE). Critical thinking provides an essential foundation for students to adapt and respond effectively to the continuous advancement of science and technology. In Plant Physiology courses, critical thinking is required not only to understand the underlying physiological mechanisms of plants but also to connect these concepts to important socio-scientific issues. This ability enables students to analyze, evaluate, and interpret physiological phenomena more deeply while recognizing their broader implications for real-world contexts. In response to this need, the study aimed to evaluate how effective the Argument-Driven Inquiry model combined with Socio-Scientific Issues (ADI-SSI) is in improving students' critical thinking skills in a Plant Physiology course.

The ADI-SSI model is an instructional innovation that integrates Argument-Driven Inquiry (ADI) with the Socio-Scientific Issues (SSI) approach. ADI is an inquiry-driven teaching approach that focuses on students actively developing claims and backing them up with evidence and logical reasoning. (Grooms et al., 2015). According to Walker et al. (2011), ADI is designed to promote conceptual understanding, inquiry skills, and critical thinking through a sequence of activities involving problem exploration, claim construction, evidence presentation, and the justification of scientific arguments in both written and oral forms. In contrast, the SSI approach centers on controversial issues that encompass scientific, social, ethical, and moral dimensions (Zeidler et al., 2019; Zeidler & Nichols, 2009). In the present study, the implementation of the ADI-SSI model began with the presentation of socio-scientific issues relevant to Plant Physiology, followed by scientific inquiry activities based on the ADI framework. The learning process ended with argumentation, a discussion of the social and ethical implications of the issues studied, and a reflection on the overall learning experience.

This study shows that using the ADI-SSI model notably enhanced students' critical thinking abilities in the Plant Physiology course. Quade's Rank ANCOVA statistical analysis showed a significant difference between the experimental and control groups when accounting for students' initial critical thinking skills. [$F(1,68) = 76.332$, $p < 0.001$, $\eta^2 = 0.53$]. An effect size of 0.53 suggests that the ADI-SSI model significantly improved students' critical thinking skills. These results align with earlier research indicating that inquiry-based learning boosts analytical skills, scientific reasoning, and science process abilities (Jannah et al., 2025; Ramadani et al., 2021). Likewise, argumentation-based learning has been shown to strengthen conceptual understanding, interpretation, and explanation skills (Melta et al., 2024), while integrating socio-scientific issues into instruction helps develop scientific reasoning and ethical decision-making. (Husniyyah et al., 2023; Mustika et al., 2025). Collectively, these competencies provide an essential foundation for developing students' critical thinking skills.

Critical thinking involves analyzing, evaluating, and interpreting information in a logical and objective manner to develop sound judgments and make informed decisions. (Altun & Yildirim, 2023; Ennis, 2011; Facione, 2011; Greenstein, 2012). This ability requires individuals to think both reflectively and rationally when addressing problems while drawing on relevant evidence to support decision-making. The process involves gathering and integrating information from multiple sources, distinguishing facts from opinions, and recognizing the biases and assumptions underlying an argument. Through these processes, individuals can draw logical, coherent, and well-justified conclusions (Murawski, 2022). This study evaluated critical thinking abilities through the FRISCO framework, which includes six indicators: focus, reason, inference, situation, clarity, and overview. (Ennis, 1993, 2011). Together, these indicators offer a thorough framework for assessing how well students can systematically apply scientific reasoning when tackling complex problems.

The ADI-SSI model proved effective in fostering all indicators of students' critical thinking skills. The most pronounced improvements were observed in the focus, situation, clarity, and overview indicators, suggesting that students became more proficient at identifying the core of a problem, considering relevant contextual factors, and constructing logical, coherent, and comprehensible explanations. Some of these improvements are due to including socio-scientific issues during the task and research question identification stage of the ADI framework. Issues such as the effects of climate change on photosynthesis and transpiration, pollution-induced physiological stress in plants, and the use of chemical fertilizers and their impact on ecosystem balance encouraged students to examine problems from both scientific and societal perspectives. Through this process, students were trained to define the focus of a problem, identify relevant information, and formulate research questions that could be investigated scientifically. More importantly, they began to recognize that phenomena in plant physiology cannot be understood in isolation from broader environmental and sustainability

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challenges. These findings align with those of Zeidler et al. (2019) and Sari et al. (2025), who found that involving students in socio-scientific issue–based learning fosters curiosity, raises environmental awareness, and enhances scientific reasoning skill.

The process of developing a method, collecting and analyzing data, and creating a tentative argument was crucial in enhancing students' critical thinking, particularly in the areas of reasoning, inference, and understanding the context. Throughout these stages, students designed investigative procedures to examine the physiological responses of plants to various environmental conditions, such as the effects of elevated temperatures on photosynthesis and transpiration rates and the impact of pollutants on plant growth and development. Collecting and analyzing empirical data encouraged students to construct logically sound explanations grounded in scientific evidence (reason) and to formulate tentative conclusions that could be empirically evaluated (inference). At the same time, integrating socio-scientific issues enabled students to interpret their findings within a broader context (situation). For example, they connected climate change–induced declines in photosynthetic efficiency with agricultural productivity and ecosystem stability. Consequently, students not only developed a deeper understanding of the causal relationships between environmental change and plant physiological responses but also strengthened their ability to reason systematically, evaluate evidence critically, and draw scientifically defensible conclusions. These results align with previously reported findings by Arifin et al. (2025), Butcher et al. (2023), and Putra & Cimari (2024), who demonstrated that critical thinking skills develop most effectively when students actively engage in scientific inquiry that is open-ended, reflective, and evidence-based.

The stages of argumentation sessions and investigation report composition were essential in enhancing students' critical thinking by improving clarity and overview. Through presentations, discussions, and the preparation of investigation reports, students practiced communicating their findings in a clear, logical, and well-structured manner (clarity). For example, they explained how rising global temperatures affect the productivity of C3 crops, such as rice, and discussed which plant species are better adapted to hot lowland environments or cooler mountainous regions. During the argumentation sessions, peer critical feedback prompted students to assess the reliability of their evidence, reevaluate their reasoning, and pinpoint weaknesses in their constructed arguments (overview).. This reflective process was further reinforced through peer review and revision of investigation reports, which provided students with opportunities to correct errors, strengthen their arguments, and critically reassess the strengths and limitations of their investigations. These results align with previous findings from Fitria et al. (2025), Paramita et al. (2025), and Songsil et al. (2019), who reported that argumentation-based instruction encourages students to participate more actively in academic discussions while enhancing their ability to construct effective written arguments. Overall, each stage of the ADI model contributed to developing all facets of critical thinking within the FRISCO framework, enabling students to focus on key problems (focus), construct logical reasons (reason), draw evidence-based inferences (inference), consider the broader context of a problem (situation), communicate ideas clearly (clarity), and critically reflect on their reasoning process (overview).

This research offers valuable insights for enhancing teaching strategies in higher education, especially within Plant Physiology courses. The results demonstrate that the ADI-SSI model can serve as an effective instructional alternative to encourage students to collect and evaluate evidence objectively, construct logical arguments, and consider multiple scientific, social, and ethical perspectives in decision-making. Through this approach, students not only gain a deeper understanding of plant physiological mechanisms, such as photosynthesis, transpiration, and hormonal responses, but also become capable of connecting these concepts to various environmental and sustainability issues faced by society. Integrating socio-scientific issues into inquiry- and argumentation-based learning also fosters an academic culture that emphasizes scientific discussion, collaboration, and critical reflection on empirical evidence. Therefore, the ADI-SSI model is worthy of broader implementation in higher education science education as an effort to create meaningful, context-based learning experiences oriented toward the development of 21st-century skills, while adhering to Outcome-Based Education (OBE) principles and promoting the achievement of Education for Sustainable Development (ESD) objectives.

This study has several limitations that need to be recognized. A small number of students (six individuals) still demonstrated critical thinking performance below the optimal category (≤75), indicating uneven adaptation to argumentation-based learning and socio-scientific issues among all participants. Variations may have influenced this condition in students' motivation, prior knowledge, and level of engagement in discussion activities. Furthermore, this study's use of the ADI-SSI model was constrained to an eight-week period; thus, this duration may be considered relatively short for the sustained and in-depth development of critical thinking skills. The limited scope of the study, which involved only one course and a single institution, should also be considered, as it suggests that the generalizability of the findings needs to be interpreted with caution.

Given these limitations, future research should extend the instructional duration and include a larger, more representative sample. Additionally, further studies could examine how the ADI-SSI model impacts students' scientific argumentation skills and scientific literacy.

CONCLUSION

This study confirms that incorporating the Argument-Driven Inquiry (ADI) model with Socio-Scientific Issues (SSI) positively influenced students' critical thinking skills in the Plant Physiology course. The analysis showed a significant difference between the experimental and control groups, with a substantial effect size. Improvements in students' critical thinking skills were evident across all FRISCO indicators, especially in the focus, situation, clarity, and overview dimensions. These findings suggest that students improved their ability to recognize problems, understand context, and develop more targeted arguments using available evidence. Additionally, incorporating the ADI-SSI model allowed students to explore social and ethical aspects of scientific argumentation, aligning the learning experience more closely with real-world biological issues.

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