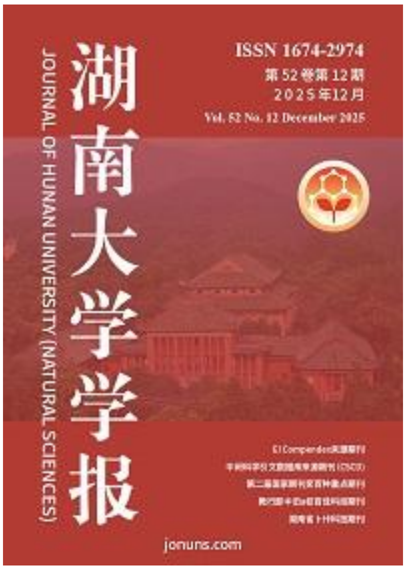

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Socioscientific Issues Based on Augmented Reality in Enhancing Students Scientific Argumentation

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Abstract: This study examines the effectiveness of a Socioscientific Issues–oriented augmented reality concept book (SSI-AR) for introductory Social Studies courses in enhancing undergraduates' scientific argumentation literacy. Employing a mixed-methods sequential explanatory design, the research involved 30 purposively selected participants. The study was conducted in three phases. During the quantitative phase, students completed pre- and post-tests following instruction using SSI-AR materials. Scientific argumentation was assessed based on the Toulmin Argumentation Pattern (TAP), encompassing claim, data, warrant, backing, and rebuttal components. Results of a paired-samples t-test indicated statistically significant improvements from pre- to post-test ($p < .05$), with overall performance increasing from a "fair" to a "good" level. The most substantial gains were observed in the claim and data components, while performance in rebuttal remained comparatively weak.

The qualitative phase, consisting of in-depth interviews, provided explanatory insights into these findings. Lower-performing students reported difficulties in accessing scholarly sources and seldom articulated counter-arguments, whereas higher-performing students actively sought additional references, leveraged AR-based simulations, and engaged in collaborative discussions. Participants further suggested the integration of multi-perspective simulations within SSI-AR to support the development of more advanced critical-thinking skills. Overall, the findings suggest that SSI-AR constitutes a promising pedagogical approach for linking abstract concepts with real-world issues, enhancing student motivation, and fostering scientific argumentation skills, while highlighting the need for explicit instructional support to strengthen rebuttal construction.

Keywords: Socioscientific issues; Augmented reality; Scientific argumentation; Toulmin argumentation pattern; Social studies education; Mixed-methods research.

基于增强现实的社会科学议题在提升学生科学论证能力中的作用

摘要：本研究旨在评估一套以社会科学议题（Socioscientific Issues, SSI）为导向并结合增强现实（Augmented Reality, AR）的概念教材（SSI-AR），用于提高本科生的科学论证能力。研究采用混合方法的顺序解释设计（mixed-methods sequential explanatory design），共纳入30名有目的抽样的参与者。研究分三个阶段进行。在定量阶段，学生在使用SSI-AR教材授课前后完成了测试，科学论证能力依据Toulmin论证模式（Toulmin Argumentation Pattern, TAP）进行评估，包括主张（claim）、证据（data）、论证（warrant）、支持（backing）和反驳（rebuttal）五个组成部分。配对样本t检验结果显示，学生在前测到后测的表现存在统计学显著提升（$p < 0.05$），总体水平从“中等”提升至“良好”。其中主张和证据部分的提升最为显著，而反驳部分仍相对薄弱。

定性阶段通过深度访谈解释了这些结果。成绩较低的学生表示难以获取学术文献，且很少提出反驳观点；而成绩较高的学生积极寻找额外参考资料，利用AR模拟进行学习，并参与协作讨论。参与者还建议在SSI-AR中加入多视角模拟功能，以促进更高阶的批判性思维能力发展。总体而言，SSI-AR被认为是一种有潜力的教学方法，能够将抽象概念与现实问题相连接，提高学生学习动机，促进科学论证能力的发展，同时提示教学中需要提供针对反驳部分的明确指导。

关键词：社会科学议题；增强现实；科学论证；Toulmin论证模式；社会研究教育；混合方法研究

1. Introduction

Rapid developments in digital technology have opened up new opportunities to improve educational quality, especially in cultivating students' critical thinking, scientific literacy, and argumentation skills. Yet, higher education often remains dominated by theory with little connection to real-life contexts, limiting students' ability to critically evaluate information, construct data-driven arguments, and make responsible scientific [1,2,3].

A promising pedagogical framework to address these challenges is Socioscientific Issues (SSI) - real-world controversies at the intersection of science and society that spark public debate. SSI-oriented learning not only builds conceptual knowledge but also nurtures reflective thinking, ethical awareness, and evidence-based reasoning [4,5]. Empirical studies show that SSI fosters functional scientific literacy and argumentation when anchored in authentic evidence and supported by structured discussions [1,2,6].

In Indonesia, Tetep (2023, 2025) highlights the strategic roleof SSI combined with Augmented Reality (AR) in advancing literacy, numeracy, and motivation [7,8]. Research demonstrates that AR-based learning media and AR-Books help bridge abstract concepts with real-world contexts, enrich reflective practice, and prepare students for 21st-century demands [7].

AR technology, by blending digital overlays with the physical environment in real time, offers immersive visualization of complex phenomena otherwise inaccessible [9,10]. Reviews confirm that AR enhances conceptual mastery, spatial reasoning, inquiry, and engagement [11,12]. When applied to SSI, AR provides authentic data, interactive simulations, and controversial scenarios that challenge students to formulate claims, marshal evidence, and counter opposing views [13,14]. Such environments, built on cognitive conflict, have been shown to elevate scientific argumentation, collaboration, and digital literacy [15,16].

In line with Tetep (2023; 2025)[7,8], integrating AR into SSI instruction represents a transformative step beyond abstract, traditional methods - fostering deeper literacy and argumentation competencies. Accordingly, this study seeks to investigate the effectiveness of AR-based SSI learning in strengthening students' scientific literacy and argumentation, vital competencies for higher education in the face of global and technological challenges.

2. Methods

This study adopted a mixed-methods approach using a sequential explanatory design, selected to gain a comprehensive view of students' scientific argumentation skills. The design begins with a quantitative phase to capture measurable outcomes and is followed by a qualitative phase to contextualize and elaborate on the numerical findings. The integration of both strands provides a deeper and more meaningful interpretation of the results.

Following Creswell and Plano Clark (2018)[37], the design proceeded through three interconnected stages:

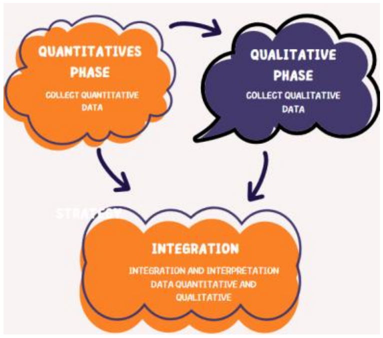
a. Quantitative Phase – Students' scientific argumentation skills were assessed through tests grounded in *Socioscientific Issues* (SSI) and enhanced with Augmented Reality (AR) media. Responses were evaluated using the Toulmin Argumentation Pattern (TAP), covering claims, data, warrants, backing, and rebuttals.

b. Qualitative Phase – Semi-structured interviews were conducted to explore students' challenges, strategies, and aspirations in formulating scientific arguments, thereby offering insights beyond test scores.

c. Integration Phase – Quantitative and qualitative findings were merged and interpreted together to construct a holistic explanation, providing both statistical trends and contextual depth.

The sequential nature of this design ensures that the qualitative insights not only support but also enrich the quantitative outcomes, leading to a nuanced understanding of students' argumentation development.

Figure 3.1 SEQUENTIAL EXPLANATORY DESIGN



Source : Creswell & Plano Clark (2018)

The study was carried out with undergraduate students enrolled in the Social Studies Education program at the Institut Pendidikan Indonesia. A total of 30 respondents were selected through purposive sampling, targeting those who had already taken the *Basic Concepts of Social Studies* course and had prior exposure to issue-based learning approaches.

Research activities were conducted in the microteaching laboratory, which was equipped with Augmented Reality (AR) tools designed to simulate various socioscientific issues. The AR media included visualizations of pressing themes such as environmental crises (e.g., plastic waste, forest fires), globalization and its socio-economic impacts, renewable energy challenges, and issues of social inequality.

The research procedure, structured within the framework of a sequential explanatory design, is outlined in Table 1, which details the phases of implementation.

Table 3.1 Mixed Methods Phase

QUANTITATIVE PHASE	QUALITATIVE PHASE	INTEGRATION/ INTERPRETATION PHASE
1 Instrument Development – An argumentation test based on Socioscientific Issues (SSI) was designed to measure students'	1 Participant Selection – Ten informants were chosen for further qualitative exploration.	2 Quantitative results (providing a profile of argumentation levels).

scientific reasoning		
3 Test Implementation by TAP Models	2. Semi-structured interviews (regarding the challenges of constructing SSI-based scientific arguments, the strategies employed, and expectations for the use of AR)	2. Qualitative results (explaining the phenomena that occurred).
3. Assessment using the TAP rubric with a 1–4 scale for each aspect. (Claim, Data, Warrant, Backing, Rebuttal).	2. Thematic Analysis (Braun & Clarke, 2006), transcription, categorial, coding and conclusion).	3. Integrative interpretation (comparing both results to achieve a comprehensive understanding).
4. Statistical Analysis (Alshorman, 2024).		

The quantitative data were analyzed using descriptive statistics—including mean, standard deviation, and percentage distributions—to provide an overview of students' performance. Where appropriate, inferential statistical tests (t-test and ANOVA) were applied to examine differences and relationships across groups. Instrument quality was established through reliability and validity testing, employing the Content Validity Index (CVI) and Cronbach's Alpha coefficients.

For the qualitative data, analysis followed two main procedures. First, a thematic analysis was conducted involving transcription, coding, categorization, and the generation of overarching themes. Second, source triangulation was applied by cross-checking test outcomes, interview data, and observational field notes. Credibility of the findings was further strengthened through data triangulation, member checking, and peer debriefing.

3. Result and Discussion

1. Research Findings

a. Quantitative Analysis Phase

1) Instrument Development

The assessment tool in this study was designed using the Toulmin Argumentation Pattern (TAP) framework, applied to *Basic Concepts of Social Studies* materials within socioscientific contexts. The socioscientific issues selected as content included natural and social phenomena such as flooding, urban heat islands, differences in urban and rural life, domestic violence, economic inequality, and educational challenges. Each issue was structured following the TAP components.

The TAP-based scientific argumentation instrument employed a four-point rubric across five elements—Claim, Data, Warrant, Backing, and Rebuttal. Validity testing confirmed that all items achieved significant item–total correlations above the critical r-value, establishing strong construct validity. Reliability testing produced a Cronbach's Alpha of 0.894, demonstrating excellent internal consistency of the instrument.

The rubric categories derived from the Toulmin model provided the primary reference for evaluating argumentation quality and served as the guiding framework for the research design.

Table 4.1 TAP Model Implementation

Claim	Data	Warrant	Backing	Rebuttal	Skor	Range
Claim is clear, specific, and aligned with the SSI-AR context..	Data is complete, relevant, and based on scientific/AR evidence.	Reasoning is logical, strongly connecting data to the claim.	Strong references/support from scientific literature/AR.	Rebuttal is clear, critically considering alternative perspectives.	4 (very good)	17-20
Claim is fairly clear and relevant.	Data is present but incomplete	Warrant is present but lacks detail	Backing is relevant but limited.	Rebuttal is present but lacks depth..	3 (good)	13-16

Claim	Data	Warrant	Backing	Rebuttal	Skor	Range
Claim is unclear.	Data is weak or does not directly support the claim	Warrant is ambiguous.	Backing is general, not scientific.	Rebuttal is minimal.	2 (enough)	10-12
Claim is not clear / not relevant.	No valid data provided	No logical reasoning provided.	No backing provided.	No rebuttal provided.	1 (less)	5-9

2) Test Administration

The instrument was implemented with 30 students through a pretest–posttest design, consisting of three main stages:

- Pretest: Administered prior to the SSI-AR intervention, using conventional learning media, to establish a baseline profile of students' scientific argumentation ability.
- Intervention: Learning activities were facilitated with SSI-AR (Socioscientific Issues with Augmented Reality), which simulated real-world socio-scientific contexts such as environmental crises, globalization, and renewable energy. Students were guided to frame their reasoning and arguments according to the Toulmin Argumentation Pattern (TAP).
- Posttest: Conducted after the intervention, employing the same instrument, in order to assess changes and improvements in students' argumentation performance.

3) Pretest–Posttest Findings Based on the Toulmin Argumentation Pattern (TAP)

a) Descriptive Analysis of Pretest and Posttest Results

Table 4.1 Analysis Pretest Postest Results
Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation
Pre_Claim	30	1	4	2.37	.809
Pre_Data	30	1	4	2.33	.711
Pre_Warrant	30	1	4	2.33	.802
Pre_Backing	30	1	4	2.40	.770
Pre_Rebuttal	30	1	3	2.10	.712
Pre_Total	30	6	18	11.53	2.874
Valid N (listwise)	30				

Source : Data Analysis SPSS 26, 2025

Based on the pre-test results, with 30 respondents, the scores ranged from a maximum of 4 to a minimum of 1 across the five dimensions (claim, data, warrant, backing, and rebuttal). The descriptive analysis revealed mean scores of 2.37 for claim, 2.33 for data, 2.33 for warrant, 2.40 for backing, and 2.10 for rebuttal. When aggregated, the respondents achieved an average total score of 11.53, reflecting the baseline level of scientific argumentation prior to the intervention.

Table 4.2 Pretest Results
Pretest_Total

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Less	9	30.0	30.0	30.0
	enough	9	30.0	30.0	60.0
	Good	11	36.7	36.7	96.7
	Very Good	1	3.3	3.3	100.0
	Total	30	100.0	100.0	

Source : Data Analysis SPSS 26, 2025

The pre-test results obtained through conventional media revealed that out of 30 respondents, 9 students were classified as "poor," 9 as "fair," 11 as "good," and only 1 as "very good." These distributions reflect the baseline profile of students' scientific argumentation skills prior to the intervention. The subsequent post-test outcomes are presented in the table below.

Table 4.3 Postest Results
Descriptive Statistics

	N	Minin	Maxir	Mean	Std. Deviati
Post_Clain	30	1	4	3.00	.788
Post_Data	30	1	4	3.00	.695
Post_Warr	30	2	4	3.03	.718
Post_Back	30	2	4	3.17	.699
Post_Rebu	30	1	4	3.03	.718
Post_Total	30	7	20	15.23	2.885
Valid (listwise)	30				

Source : Data Analysis SPSS 26, 2025

The post-test results involving 30 respondents show that scores for claim, data, and rebuttal ranged from a minimum of 1 to a maximum of 4, while warrant and backing ranged from 2 to 4. Descriptive statistics indicate mean scores of 3.00 for claim, 3.00 for data, 3.03 for warrant, 3.17 for backing, and 3.03 for rebuttal. Collectively, these yielded an average total score of 15.23, reflecting a marked improvement in students' scientific argumentation performance compared to the pre-test.

Table 4.4 Total Postest Analysis Results

Postest_Total

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Less	1	3.3	3.3	3.3
	Enough	5	16.7	16.7	20.0
	Good	17	56.7	56.7	76.7
	Very Good	7	23.3	23.3	100.0
	Total	30	100.0	100.0	

Source : Data Analysis SPSS 26, 2025

The post-test results with SSI-AR media showed a clear improvement in students' scientific argumentation abilities. Of the 30 respondents, only 1 student fell into the "poor" category, 5 students into the "fair" category, while the majority—17 students—were in the "good" category, and 7 students reached the "very good" category.

When compared with the pre-test outcomes, the descriptive analysis highlights a notable upward shift. In the pre-test, the distribution was 9 students "poor," 9 students "fair," 11 students "good," and 1 student "very good." By contrast, in the post-test the "poor" group declined sharply (from 9 to 1), the "fair" group reduced from 9 to 5, the "good" category increased from 11 to 17, and the "very good" category rose substantially from 1 to 7 students. This pattern confirms that SSI-AR–based learning enhanced students' argumentation performance more effectively than conventional methods.

b) Inferential Analysis (Pre-test vs. Post-test)

Normality testing using the Kolmogorov-Smirnov test confirmed that the data followed a normal distribution (p = 0.24 > 0.05). Consequently, further analysis was conducted with the Paired Samples t-test to evaluate the significance of differences between pre-test and post-test scores.

Table 4.5 Significance Test Analysis

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
					95% Confidence Interval of the Difference				
		Mean	Std. Deviation	Std. Error Mean	Lower	Upper			
Pair 1	Pre_Total - Post_Total	-3.700	4.260	.778	-5.291	-2.109	-4.757	29	<,001

Source : Data Analysis SPSS 26, 2025

The statistical analysis revealed a p-value of 0.001 (< 0.05), indicating a significant difference between pre-test and post-test results. This confirms that SSI-AR–based instruction effectively enhanced students' scientific argumentation abilities.

c) Gender-Based Analysis

Beyond the comparison of pre- and post-test scores, an additional analysis was performed to examine potential differences across male and female students using the Independent Samples t-test.

Table 4.6 Gender Based Analysis

Group Statistics

	Gender	N	Mean	Std. Deviation	Std. Error Mean
Pre_Total	Men	15	11.73	2.052	.530
	Woman	15	11.33	3.579	.924
Post_Total	Men	15	15.80	3.509	.906
	Woman	15	14.67	2.059	.532

Source : Data Analysis SPSS 26, 2025

Table 4.7 Significance Level Analysis
Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Pre_Total	Equal variances assumed	5.045	.033	.376	28	.710	.400	1.065	-1.782	2.582
	Equal variances not assumed			.376	22.305	.711	.400	1.065	-1.807	2.607
Post_Total	Equal variances assumed	.931	.343	1.079	28	.290	1.133	1.050	-1.018	3.285
	Equal variances not assumed			1.079	22.616	.292	1.133	1.050	-1.042	3.308

Source : Data Analysis SPSS 26, 2025

The analysis revealed a significance level of 0.033 (< 0.05) for the pre-test, indicating a statistically significant difference in scientific argumentation between male and female students when using conventional media. In contrast, the post-test yielded a significance level of 0.343 (> 0.05), showing no gender-based difference in the SSI-AR condition. These findings suggest that SSI-AR fosters equitable improvements in scientific argumentation, unaffected by gender.

b. Qualitative Phase

1. Respondent Selection and Interview Insights

Ten students representing high, medium, and low performance groups were purposively selected for semi-structured interviews. Their reflections provided deeper insights into how they experienced argumentation development while engaging with SSI-AR–enhanced learning in the *Basic Concepts of Social Studies* course. Thematic analysis revealed three overarching themes: challenges, strategies, and expectations. These insights not only captured students' perceptions but also demonstrated how AR integration within SSI contexts influences the quality of their argumentation. The results are further discussed in relation to international scholarship on AR, information literacy, and SSI pedagogy to highlight implications for instructional design and future research.

2. Challenges in Developing Arguments

A recurring difficulty, particularly among lower-performing students, was the inability to identify and use relevant scientific data to substantiate claims. Many admitted to relying on personal opinion without sufficient credible evidence, echoing findings in information literacy research that emphasize the central role of accessing, evaluating, and applying reliable scientific sources in evidence-based reasoning (Nagpal et al., 2023)[42]. Limited information literacy thus constrained students' ability to construct convincing arguments.

Another prominent challenge lay in the rebuttal stage. Students often lacked experience in evaluating counterarguments, tending to stop at stating claims and presenting supporting data without addressing alternative viewpoints. Scholarship in SSI-based argumentation identifies rebuttals as the most demanding component, requiring multi-perspective thinking, evaluation of opposing evidence, and integration of divergent perspectives (Olokunde, 2023)[43]. Students' weaknesses in this regard reflect academic habits that prioritize claims over counterarguments.

Incorporating AR technology into SSI instruction presents a promising solution. AR provides integrated access to diverse data, visual representations, and simulated scenarios, enabling richer engagement with evidence. Studies demonstrate that AR can foster motivation and positive learning attitudes (Abdilah & Suhardiyanto, 2023)[44] while bridging abstract data with real-world contexts (Szentirmai & Murano, 2024)[45]. These affordances can help students strengthen both the evidentiary basis of their claims and their capacity to formulate rebuttals.

In sum, the qualitative findings underscore how gaps in information literacy and a claim-centered learning culture limit the depth of students' argumentation. At the same time, they point to the transformative potential of AR-based scaffolds and counterargument simulations to push students beyond surface-level reasoning and toward more sophisticated scientific argumentation.

3. Student Strategies

High-achieving students employed systematic and diverse strategies in building arguments. They actively consulted scientific literature—including articles, reports, and statistical datasets—to substantiate their claims. This aligns with research in information literacy, which underscores the importance of credible sources in producing high-quality arguments (Nagpal et al., 2023)[42].

Students also leveraged AR simulations to anchor their reasoning in real-world contexts, such as environmental crises or globalization. These interactive scenarios helped them frame arguments that were more contextualized and relevant. Yadav (2025)[46] similarly argued that problem-based AR scenarios enhance relevance, motivation, and depth of cognitive processing.

Another prominent strategy was small-group collaboration. Students who performed well typically discussed issues with peers before writing, benefiting from feedback, exposure to multiple perspectives, and iterative refinement of claims and evidence. Prior studies confirm that collaborative dialogue strengthens argumentation by encouraging students to compare, test, and reinforce their reasoning (Nagpal et al., 2023)[42].

From a pedagogical standpoint, these strategies can be further reinforced by designing collaborative AR activities, such as group projects that require accessing credible data through AR, engaging in verification discussions, and collectively drafting arguments. Empirical work (Abdilah & Suhardiyanto, 2023)[44] highlights that AR combined with collaborative learning fosters critical and reflective engagement.

Taken together, these strategies demonstrate consistency with AR-based pedagogy, where evidence gathering, real-world contextualization, and collaboration serve as cornerstones of strong argumentation.

4. Expectations for SSI-AR

Students articulated several expectations for future applications of SSI-AR. They expressed interest in interactive "what-if" simulations, for instance, renewable energy policies, which would allow them to examine alternative solutions and their consequences. Such expectations align with Yadav's (2025)[46] findings that AR can deepen critical engagement through policy-driven scenario exploration.

They also viewed AR as a medium to bridge abstract data with real-world problems, echoing research that emphasizes AR's role in fostering contextual understanding and engagement (Abdilah & Suhardiyanto, 2023)[44]. Furthermore, Kapetanaki et al. (2021)[47 demonstrated that pedagogically designed AR can improve comprehension for diverse learners, including those with special needs, suggesting AR's adaptability across student populations.

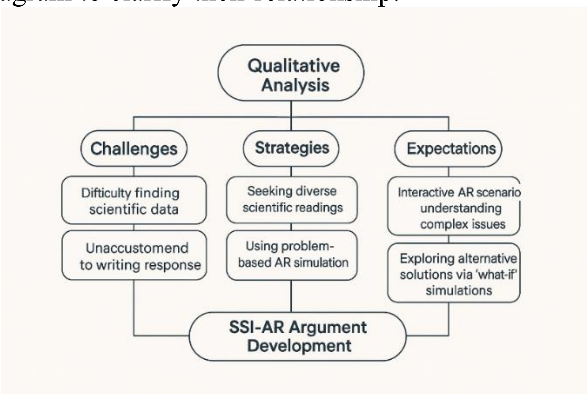
Students further hoped for broader coverage of socioscientific scenarios, including climate change, public health, and other global issues. This indicates their recognition of AR not merely as a visualization tool, but as a policy-exploration platform that enables practice in evidence-based decision-making within complex contexts.

5. Thematic Insights

The thematic analysis synthesized students' experiences into three central patterns:

- Challenges: limited information literacy and difficulties in formulating rebuttals.
- Strategies: reliance on scientific evidence, use of AR simulations, and collaborative discussion.
- Expectations: richer interactive scenarios and stronger connections between abstract data and real-world issues.

These interconnected themes illustrate how SSI-AR learning environments shape argumentation quality. The interplay between empirical findings and theoretical perspectives is presented through a visual diagram to clarify their relationship.



c. Integration of Quantitative and Qualitative Results

The quantitative findings placed students' argumentation ability in SSI-AR learning within the fair-to-good range, with the most pronounced weakness in rebuttal construction. This was corroborated qualitatively, as students themselves admitted difficulties in locating relevant literature to support counterarguments. Hence, the weakness reflects not merely cognitive limitations but also constraints in information access and entrenched academic practices that emphasize claims over counter-evidence (Olokunde, 2023; Nagpal et al., 2023)[43'42].

This integrative conclusion aligns with wider scholarship showing how information literacy skills and learning habits critically influence the quality of scientific argumentation in AR-based environments. Prior work demonstrates that AR, when carefully designed, enhances engagement, scaffolds evidence-based reasoning, and promotes multi-perspective evaluation. Abdilah & Suhardiyanto (2023)[44], for instance, reported that AR can bridge scientific data with social phenomena, motivating students to rely more heavily on concrete evidence.

Triangulating quantitative and qualitative data strengthens the interpretation that SSI-AR's effectiveness does not stem from technological novelty alone, but from its instructional design quality. While AR enriches engagement and contextual understanding, its potential to improve rebuttals depends on the presence of information-literacy scaffolds, accessible scholarly resources, and structured opportunities to practice counterargumentation (Olokunde, 2023; Abdilah & Suhardiyanto, 2023; Nagpal et al., 2023)[43,44,42].

Thus, SSI-AR is shown to enhance students' scientific argumentation, but robust, multi-perspective reasoning requires instructional approaches that integrate explicit information-literacy training and deliberate rebuttal practice.

Discussion

Overall, the study demonstrates that SSI-AR significantly strengthens scientific argumentation skills. Quantitative evidence revealed consistent and statistically significant gains from pre-test to post-test, particularly in claims, data, warrants, and backing, while rebuttals remained an area of weakness despite modest improvements. Qualitative insights reinforced this, with students citing limited access to scholarly sources and claim-centered academic habits as obstacles. Together, the triangulated findings suggest that SSI-AR's strength lies in providing authentic, contextualized scenarios that support the formulation of claims and data, although sustained development of rebuttals requires explicit instructional intervention.

The marked improvements in claims and data can be interpreted through prior literature that highlights AR's pedagogical power in visualizing complex issues. Cheng and Tsai's (2021)[41] meta-analysis found that AR consistently bridges abstract concepts with real-world experiences, thereby enhancing conceptual understanding. Similarly, Ibáñez and Delgado-Kloos (2018) underscored AR's ability to raise motivation and deepen cognitive engagement. In this study, AR-based simulations of renewable energy challenges and environmental crises allowed students to contextualize arguments, producing claims that were both stronger and more evidence-based. As Zeidler (2014) [48] and Sadler & Zeidler (2005)[5] argue, the essence of scientific literacy in SSI learning lies in connecting data with the social, ethical, and moral dimensions of issues. The observed improvements in claims and data thus signal that SSI-AR achieved its pedagogical goal of linking science to real-world societal concerns.

The rebuttal weakness highlights AR's limitations when not paired with instructional designs that foster information literacy and multiperspective reasoning. Toulmin (2003)[49] underscores rebuttal as an essential component of high-quality argumentation, requiring the evaluation of counter-evidence and critical engagement with claims. In this study, low rebuttal scores were echoed in student interviews, where many reported difficulty locating relevant literature and admitted they were unaccustomed to formulating counterarguments. These findings align with Olokunde (2023)[43], who identified rebuttal as the most complex element of scientific argumentation, and with Osborne et al. (2016)[33] and Erduran et al. (2015)[28], who view it as a key indicator of argumentation development. Thus, while AR enhances claims and data, robust argumentation requires explicit scaffolding and targeted practice in rebuttal construction.

High-performing students' strategies also explain score variations. Those who scored well reported actively seeking scholarly readings, engaging in small-group discussions, and leveraging AR simulations to contextualize arguments. Such behaviors reflect Nagpal, Rahmawati, and Mardiah (2023)[42], who argue that information literacy and engagement with credible sources are essential for high-quality argumentation. Group dialogue further strengthened reasoning, consistent with Berland & Hammer's (2011)[30] view that collaborative exchanges allow students to test, refine, and reinforce arguments, and Dawson & Venville's (2010) [3] finding that peer interaction expands exposure to alternative perspectives. These strategies explain why high performers produced stronger, more evidence-rich arguments.

Students' expectations for SSI-AR extended beyond visualization. Many expressed interest in multiperspective or "what-if" simulations that would allow exploration of alternative policy solutions, viewing AR as a medium for evidence-based decision-making in complex contexts. Yadav (2025)[46] similarly noted that problem-based AR scenarios enhance emotional engagement and higher-order critical thinking. Such expectations point to future SSI-AR designs that incorporate richer, interactive multiperspective simulations to foster advanced argumentation.

The integration of quantitative and qualitative results revealed consistent triangulation. Quantitative improvements in claims, data, and backing were mirrored by qualitative reports of strategies such as seeking readings and using AR simulations, while weaknesses in rebuttal corresponded with reported challenges in counterargument construction. This demonstrates that SSI-AR's effectiveness lies in providing concrete contexts for claim and data construction, but achieving multiperspective reasoning requires more explicit pedagogical design. As Fetters, Curry, and Creswell (2013)[52] note, mixed methods' strength lies in their ability to yield comprehensive insights through integration—a principle clearly exemplified in this study.

Theoretically, this research contributes to scientific argumentation and SSI-AR pedagogy, affirming Toulmin's (2003)[49] emphasis on rebuttal and supporting the view of AR as a cognitive scaffold (Szentirmai & Murano, 2024; Vee & Zhai, 2017)[45,50]. It also corroborates Akçayır & Akçayır (2017)[12], who argue that AR's educational value depends on instructional designs that promote critical and reflective thinking. Practically, the study underscores that SSI-AR's success is determined not by technology alone but by pedagogical design quality, emphasizing information literacy, multiperspective collaboration, and explicit rebuttal practice.

The study's limitations include its relatively small sample size and reliance on simple marker-based AR, which restrict generalizability. Future research should test SSI-AR using mixed reality or AI-driven AR to expand access to scholarly resources. Further interventions should explicitly scaffold rebuttal construction through information literacy training, as recommended by Onwuegbuzie & Leech (2006) [51]in the context of mixed methods.

In conclusion, SSI-AR emerges as a transformative pedagogical approach that bridges abstract concepts with real issues, strengthens claims and data through interactive visualization, and enhances motivation and cognitive engagement. Yet, full effectiveness requires pairing AR with instructional strategies that target information literacy, multiperspective collaboration, and rebuttal practice. Properly designed, SSI-AR is not merely a visualization tool but a comprehensive learning framework that equips students with critical, reflective, and collaborative thinking skills essential for the 21st century.

5. Conclusion

This study confirmed that SSI-AR significantly improves students' scientific argumentation skills. Quantitative results showed notable pre–post test gains, moving from "fair" to "good," especially in claim, data, warrant, and backing, though rebuttal remained weak. Qualitative findings reinforced these patterns, with lower achievers struggling to find scholarly sources while higher performers actively sought evidence, used AR simulations, and engaged in group discussion. Students also expressed expectations for multiperspective simulations, viewing AR as a tool for practicing evidence-based decision-making.

Overall, SSI-AR can be regarded as a transformative approach that links abstract science concepts with real-world issues, increases motivation, and strengthens argumentation. However, achieving comprehensive argumentation quality requires explicit instructional focus on rebuttals and multiperspective reasoning.

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