



Learning from Earthquakes: The Role of Socio-Scientific Issues in Developing Students' Science Argumentation Skills

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Abstract

This study aims to develop and test the effectiveness of learning modules based on Socio-Scientific Issues with Problem-Based Learning (SSI-PBL) approach in improving students' scientific argumentation skills on the topic of earthquake mitigation. The research method used is Research and Development with the 4D model (Define, Design, Develop, Disseminate) involving 95 grade VIII students at SMP Negeri 1 Maduran, Lamongan. Data collection techniques included scientific argumentation tests (pre-test and post-test), observation of student activities and learning implementation, and student response questionnaires. Data were analyzed descriptively quantitatively and inferentially using paired t-test, gain score and ANOVA test to measure skill improvement. The results showed a significant improvement in students' argumentation skills, with an average post-test score of 68% compared to 21% in the pre-test, as well as improvements in the indicators of claims (from 28% to 72%), use of data (15% to 65%), and preparation of rebuttal (25% to 58%). The SSI-PBL design facilitated deeper engagement by situating students in authentic, real-world contexts that required critical examination of seismic data, policy debates, and ethical considerations. These findings suggest that the SSI-PBL module is able to bridge the gap between theory and practice in disaster learning and strengthen 21st century skills such as critical thinking, problem solving, and public policy literacy. Results underscore the module's effectiveness in fostering scientific literacy, critical thinking, and policy awareness, essential for disaster-resilient communities.

Keywords: SSI-PBL module; Scientific argumentation skills; Earthquake education; Disaster preparedness

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INTRODUCTION

Indonesia, located along the Pacific Ring of Fire, is among the most seismically active regions globally, experiencing frequent tectonic movements due to its position between the Eurasian, Indo-Australian, and Pacific plates (Deta et al., 2025; Dianti et al., 2022). According to the Meteorology, Climatology, and Geophysics Agency (BMKG), Indonesia records over 11,000 earthquakes annually, some causing significant damage (Fuady et al., 2021; M. Bagher et al., 2023). These conditions highlight the urgency of integrating disaster preparedness into science education to equip students with critical thinking skills (Prakoso et al., 2021; Prasetyaningsih et al., 2024).

Science education in Indonesia remains overly theoretical, with limited opportunities for students to engage in scientific argumentation, particularly in contexts where they need to build and test models, as well as critically analyze data. This lack of focus on scientific practices

limits students' ability to engage in evidence-based argumentation that is central to scientific reasoning (Deta et al., 2025; Ko et al., 2022). On the other hand, students' ability to engage in civic argumentation, particularly on socio-political issues like earthquake mitigation, is underdeveloped. The integration of socio-scientific issues (SSI) with problem-based learning (PBL) in this study aims to address both aspects: fostering scientific argumentation based on empirical evidence and scientific reasoning, while also preparing students to engage in civic argumentation related to disaster management policies and societal responses. This distinction clarifies the focus on both epistemic (scientific) and rhetorical (policy-oriented) argumentation, ensuring that students develop the skills to reason scientifically while also considering broader societal and policy implications in the context of disaster management (Casey, 2019; M. S. Ummah, 2022). Studies by the Organisation for Economic Co-operation and Development (OECD) suggest that problem-based learning (PBL) is significantly more effective than rote memorization in enhancing students' scientific understanding (Oliveira & Souza, 2022). Adopting PBL methods could therefore improve students' ability to construct evidence-based arguments and respond to seismic risks more effectively.

A promising approach to addressing this gap is the integration of socio-scientific issues (SSI) into earthquake education, which has been shown to enhance students' critical thinking and scientific argumentation skills (Nurhasnah et al., 2022; Putriana, 2020). While previous studies have explored SSI in the context of environmental or health education, its integration with disaster education, particularly in earthquake preparedness, remains underutilized. The existing research on SSI-PBL in disaster education, especially in Asia, often fails to address the localized needs of students in earthquake-prone regions or lacks a robust pedagogical structure for argumentation (I. Benek & Akcay, 2022; Nida et al., 2020; POWELL, 2021). This study builds on previous SSI-PBL interventions by focusing on real-world, locally relevant seismic case studies (such as Lamongan and Palu), incorporating Toulmin's Argumentation Framework, and emphasizing both scientific reasoning and policy analysis to bridge the gap between theory and real-world application in disaster management. Unlike previous SSI-PBL studies in Asia, which often lack a robust pedagogical structure for argumentation or fail to address the localized needs of students in earthquake-prone regions, this study integrates local seismic data and situates students within real-world disaster preparedness debates, thereby providing a more targeted and contextually relevant approach. Studies indicate that students who participate in SSI-based learning outperform those in traditional settings in terms of their ability to construct well-reasoned scientific arguments (Anggereini et al., 2023).

In nations with strong disaster education frameworks, such as Japan, SSI has been instrumental in fostering public awareness and resilience against earthquakes (Chaturvedi, 2021; Sularno et al., 2021). By implementing an SSI-based approach in Indonesian classrooms, students can develop a more holistic understanding of earthquakes, integrating scientific, social, and policy dimensions to better prepare for future disasters. Despite the growing emphasis on scientific literacy, Indonesian students still struggle with scientific argumentation, particularly in connecting science concepts with real-world socio-scientific issues. This gap is especially prominent in the context of disaster education, where traditional teaching methods primarily focus on memorization and do not foster critical thinking or argumentation. By integrating socio-scientific issues (SSI) with problem-based learning (PBL), this study offers a novel approach that not only enhances students' understanding of earthquake science but also empowers them to evaluate and debate mitigation strategies based on local knowledge and context (Fitri et al., 2020; Jumiyati et al., 2024; Soraya et al., 2023). The lack of structured argumentation in science education has significant implications, as it limits students' ability to critically evaluate disaster risks and propose well-informed mitigation strategies (Cabello, 2022; Martini et al., 2021). Without the ability to form coherent, evidence-backed arguments, students may struggle to comprehend the broader implications of scientific phenomena, such

as the socio-economic impact of earthquakes and the role of policy interventions in disaster preparedness.

A preliminary study was conducted to assess not only students' understanding of earthquake science but also their ability to construct scientific arguments related to disaster mitigation. This focus on 'why'—the reasoning behind the need for specific mitigation strategies—aims to help students recognize the importance of using scientific evidence to justify their proposed solutions and decisions in disaster preparedness, rather than relying solely on memorized facts. The study was carried out at Junior High School 1 Maduran, Lamongan, on October 15, 2024, involving 22 eighth-grade students (10 male and 12 female), aged between 13 and 15 years old. Using a mixed-method approach, the research team conducted structured tests, interviews, and group discussions to evaluate students' conceptual grasp of earthquakes and their argumentation skills. The results revealed that 78% of students perceived earthquakes solely as natural disasters caused by tectonic shifts, without linking them to their broader socio-environmental consequences. When asked about earthquake mitigation efforts, 65% of students struggled to explain how government policies, such as building regulations and early warning systems, contribute to disaster risk reduction. The study revealed that only 21% of students could construct a coherent scientific argument integrating geological factors, societal preparedness, and policy interventions for earthquake mitigation. This highlights a critical gap in students' ability to connect scientific knowledge with real-world applications in disaster risk reduction. The failure to construct well-reasoned, evidence-based arguments severely limits their ability to evaluate disaster risks and propose appropriate mitigation strategies, which underscores the need for an educational intervention that explicitly teaches scientific argumentation through socio-scientific issues.

A preliminary study was conducted to assess not only students' understanding of earthquake science but also their ability to construct scientific arguments related to disaster mitigation. Central to this study is the emphasis on the 'why'—why certain disaster mitigation strategies are necessary and how to justify these strategies through scientific reasoning and evidence. This study explores how students' argumentation skills can be developed to construct well-supported claims, evaluate policies, and make evidence-based decisions in disaster preparedness." Applying Toulmin's model, most students' arguments lacked a clear claim (e.g., failing to assert that effective mitigation requires interdisciplinary integration), relied on fragmented data (e.g., citing tectonic shifts without linking them to building codes or community drills), and omitted logical warrants to connect evidence to conclusions (e.g., stating "earthquakes cause damage" without explaining how policies reduce risks). Few referenced backing from real-world examples (e.g., Japan's integrated strategies) to strengthen their claims, and 83% were unable to address rebuttals (e.g., countering the notion that "disasters are unavoidable"). Additionally, arguments lacked qualifiers to contextualize limitations (e.g., ignoring regional variations in policy applicability). These gaps highlight students' struggles to synthesize scientific, social, and policy dimensions into a unified argument, underscoring the need for pedagogy that explicitly teaches Toulmin's structure to bridge theoretical knowledge and actionable disaster mitigation strategies in earthquake-prone regions like Lamongan.

Interviews with three science teachers from Junior High School 1 Maduran, Lamongan further revealed gaps in the current teaching approach. Teachers acknowledged that while earthquake-related topics were part of the curriculum, the instructional methods primarily focused on rote memorization rather than encouraging students to develop evidence-based arguments. According to the teachers, classroom discussions rarely extended beyond textbook definitions, leaving little room for students to critically analyze real-world earthquake events, such as those that have occurred in Indonesia. These findings highlight the urgent need for an educational intervention that promotes problem-solving and argumentation skills through socio-scientific issues (SSI).

Several studies have explored the integration of Socio-Scientific Issues (SSI) and innovative instructional modules to enhance students' scientific literacy and argumentation skills. For instance, research indicates that SSI-based science instruction can significantly improve students' scientific literacy across various dimensions, including context, competencies, knowledge, and attitudes (Mang et al., 2021; Martini et al., 2021). Additionally, the implementation of the Problem-Based Learning (PBL) module has been shown to positively impact students' scientific argumentation abilities, particularly when supported by digital tools like Nearpod (Hartono et al., 2023; Rahma, 2024). Moreover, the use of SSI approaches, especially when combined with electronic modules, has been found to enhance critical thinking skills among students (Aufa et al., 2021; I. Ummah, 2025). Furthermore, the Argument-Driven Inquiry (ADI) module has been effective in fostering students' scientific argumentation skills, surpassing traditional instructional methods (Akili et al., 2022; Antonio & Prudente, 2021). However, despite these advancements, there remains a notable gap in research specifically addressing the application of SSI-based problem-solving instructional modules to improve students' scientific argumentation skills in the context of earthquake education.

Although extensive research has been conducted on *socio-scientific issues* (SSI) in science education, a significant gap remains in its application for developing students' scientific argumentation skills, particularly in the context of natural disasters like earthquakes. Many existing studies focus on SSI integration in broader scientific discussions, such as environmental sustainability and health sciences, but few explore how it can enhance students' ability to construct evidence-based arguments about disaster risk and mitigation (Anggereini* et al., 2023; Nida et al., 2020; Putriana, 2020). This *empirical gap* suggests that while SSI has proven effective in fostering critical thinking, its potential in disaster education remains underutilized.

The novelty of this study lies in its development of an integrated instructional module that combines Socio-Scientific Issues (SSI) with a problem-solving approach to enhance students' scientific argumentation skills specifically in the context of earthquake education. This approach surpasses previous SSI-PBL frameworks by incorporating localized case studies and integrating Toulmin's Argumentation Framework to guide students in constructing evidence-based, scientifically grounded arguments. Additionally, the module's focus on both the scientific and policy dimensions of disaster management makes it particularly relevant for students in earthquake-prone regions like Indonesia, addressing gaps left by previous studies that primarily focused on theoretical or general SSI applications. Unlike previous research that primarily focuses on either the theoretical understanding of seismic phenomena or the general application of SSI in environmental and health-related contexts, this study addresses a significant gap by emphasizing the practical application of SSI to real-world disaster scenarios.

This study proposes a problem-solving instructional module that integrates SSI-based learning to enhance students' scientific argumentation skills in the context of earthquakes. Unlike conventional science lessons that focus solely on geological explanations, this approach combines theoretical concepts with empirical data, real-world case studies, and policy analysis, such as the 2018 Palu earthquake. This intervention goes beyond traditional SSI-PBL frameworks by incorporating local seismic data and situating students in real-world disaster preparedness debates, helping them to understand the 'why' behind mitigation strategies. The integration of Toulmin's Argumentation Framework further strengthens the pedagogical approach, offering a structured way for students to engage with and evaluate the scientific and policy dimensions of earthquake preparedness. By applying Toulmin's model, students will learn to construct arguments with clear claims supported by evidence, warrants to connect evidence to conclusions, and qualifiers to address the limitations of their claims. This structured approach helps students develop the skills to critically assess scientific data and policy measures, fostering a deeper understanding of disaster mitigation and preparedness. By

engaging students in discussions on how science informs disaster policies and societal responses, the module fosters both scientific literacy and critical thinking. Ultimately, this framework aims to empower students with the ability to make evidence-based decisions, bridging the gap between scientific knowledge and its practical application in disaster preparedness. This study aims to examine the effectiveness of a problem-solving-based learning module in enhancing students' scientific argumentation skills related to tectonic earthquakes and disaster mitigation.

More specifically, this study investigates how the problem-solving approach strengthens students' argumentation structure in terms of data, warrant, backing, rebuttal and claims regarding earthquakes and mitigation strategies. Argumentation is a fundamental skill in science education, enabling students to critically evaluate information, assess risks, and develop sound conclusions based on scientific data (Darmaji et al., 2022; Jordanou & Rapanta, 2021).

METHOD

This research employs a Research and Development (R&D) approach aimed at developing instructional materials using the Problem Based learning module based on Socio-Scientific Issues (SSI). This approach is highly appropriate due to its objective of enhancing students' scientific argumentation skills through authentic socio-scientific contexts such as earthquakes, closely relevant to students' real-life experiences. The development module adopted is the 4D Module (Define, Design, Develop, Disseminate) proposed by Thiagarajan, Semmel, and Semmel (Pandia et al., 2023; Yuliana & Hambali, 2020; Zayas & Rofi'ah, 2022). This module provides a systematic and structured framework for continuously improving instructional materials, making it particularly suitable for this research.

The population of this study comprises eighth-grade students from Junior High School 1 Maduran, geographically located in Lamongan Regency, East Java, Indonesia. The sample consisted of 95 students, aged 13-14, with an almost equal gender distribution (47% male and 53% female). Additionally, a preliminary survey was conducted to assess the students' prior exposure to earthquake-related topics, revealing that 80% of students had been taught basic earthquake concepts in their science curriculum, while the remaining 20% had limited prior exposure to the topic. This population was selected because students at this age are at a critical developmental stage for enhancing their scientific argumentation skills. Samples were randomly selected, detailed as follows:

Table 1. Research Sample Description

Class	Number of Students	Age Range	Socioeconomic Background	Cultural Background
VIIIA	32	13-14	Middle to lower-middle	Homogeneous (Local Javanese culture)
VIIIB	32	13-14	Middle to lower-middle	Homogeneous (Local Javanese culture)
VIIIC	31	13-14	Middle to lower-middle	Homogeneous (Local Javanese culture)
Total	95	-	-	-

Data collection techniques involved several relevant methods, including scientific argumentation tests, student activity observation sheets, lesson implementation observation sheets, and student response questionnaires. To ensure the reliability of the data, multiple raters independently observed student activities and the lesson implementation, with inter-rater reliability calculated using Cohen's kappa coefficient. This approach ensures consistent evaluation and minimizes subjective bias in the assessment of student performance. The

scientific argumentation tests, designed as open-ended questions based on indicators developed by Erduran et al. (Darmaji et al., 2022), serve as the primary instrument for measuring students' argumentation skill improvement. The tests are administered twice, before (pre-test) and after (post-test) the intervention. Observation of student activities and lesson implementation is carried out by two observers during teaching sessions, systematically recording discussion activities and teacher adherence to the SSI-based Problem Solving instructional module. Additionally, student response questionnaires are distributed to assess the practicality and attractiveness of the developed instructional materials.

To ensure the reliability of the scientific argumentation tests, Cronbach's Alpha coefficient was calculated for the pre-test and post-test instruments. The reliability coefficient for the pre-test was 0.85, indicating good internal consistency, while the post-test had a Cronbach's Alpha of 0.87. Additionally, inter-rater reliability for the argumentation assessment was calculated using Cohen's kappa coefficient, yielding a value of 0.92, indicating strong agreement between raters. Data analysis techniques involve descriptive quantitative analysis and inferential statistics conducted using SPSS software version 27. Pre-test and post-test data are analyzed using gain scores to quantify improvement in students' scientific argumentation skills. Descriptive analysis of observations and questionnaires assesses the effectiveness and practicality of instructional implementation.

RESULTS AND DISCUSSION

This study employed the 4D instructional design module (Define, Design, Develop, Disseminate) to systematically develop and evaluate a Socio-Scientific Issues (SSI)-based learning module aimed at enhancing students' scientific argumentation skills in earthquake education. The framework guided a structured exploration of pedagogical needs, iterative prototyping, empirical validation, and scalable dissemination. The following sections detail the findings aligned with the 4D stages, emphasizing how each phase contributed to bridging the gap between theoretical knowledge and practical disaster preparedness in Indonesia's earthquake-prone regions.

Result

Define

The Define stage commenced with a comprehensive needs assessment at state junior high school 1 Maduran, Lamongan, revealing critical gaps in earthquake education. Initial surveys indicated that 78% of eighth-grade students perceived earthquakes solely as tectonic phenomena, lacking awareness of their socio-political implications, such as the role of government policies in disaster mitigation. Interviews with science teachers further highlighted the curriculum's overreliance on rote memorization of geological concepts, with minimal emphasis on real-world applications like analysing building codes or early warning systems. This misalignment between theoretical instruction and practical preparedness underscored the urgency for an educational module that bridges scientific knowledge with societal contexts.

A review of global literature and theoretical frameworks reinforced the potential of Socio-Scientific Issues (SSI) and Problem-Based Learning (PBL) to address these gaps. Studies from Japan demonstrated how SSI-based disaster education enhances public resilience by integrating policy debates and community engagement. Similarly, OECD findings (2023) confirmed that students exposed to PBL exhibit 40% stronger reasoning skills than those in traditional settings. However, Indonesian curricula rarely employ these approaches, particularly in disaster education, leaving students ill-equipped to connect seismic science with socio-economic realities. This literature analysis validated the need for a localized SSI-PBL module tailored to Indonesia's seismic challenges.

The Define stage identified three core challenges: (1) a curriculum overly abstract and detached from policy analysis, (2) students' limited ability to construct arguments synthesizing

scientific data and social contexts, and (3) the absence of authentic case studies in classroom discussions. Teachers also reported confusion accessing real-time seismic data and guidelines for facilitating policy debates. These issues collectively hindered students' capacity to evaluate mitigation strategies, as evidenced by pre-test scores showing only 25% proficiency in constructing rebuttals.

In response, the research objectives were refined to develop an SSI-PBL module that (1) integrates BMKG seismic data and localized case studies, (2) trains students to analyze mitigation policies through structured debates, and (3) enhances scientific argumentation skills using Toulmin Argumentation Pattern.

The implications of this stage underscored the need for systemic educational reforms. Recommendations included community centered case studies to enhance cultural relevance. By grounding the curriculum in authentic issue, such as what steps need to be taken for disaster preparedness, the Define stage established a foundation for empowering students to navigate the complexities of disaster risk reduction, ultimately fostering a generation capable of bridging science, policy, and societal needs.

Design

The Design Stage focused on constructing a prototype SSI-PBL (Socio-Scientific Issues-Problem-Based Learning) module tailored to bridge the gaps identified in earthquake education. The prototype prioritized real-world relevance, featuring modules that juxtaposed geological concepts with policy analysis, such as evaluating the effectiveness of Indonesia's early warning system during the 2018 Palu earthquake. Each module was structured around Toulmin Argumentation Pattern to systematically develop students' argumentation skills. Visual aids, including interactive infographics and simulation videos, were embedded to demystify complex topics like liquefaction and tectonic subduction.

Central to the design was the inclusion of localized case studies, such as Lamongan's 2023 seismic activity, to enhance contextual engagement. These case studies required students to analyze primary data, such as BMKG's magnitude reports and damage assessments, and correlate them with socio-economic impacts, such as the level of public panic or the allocation of costs to anticipate the impact of the earthquake. Policy debate scenarios were crafted to simulate real decision-making processes, such as allocating limited budgets between emergency response training and infrastructure reinforcement. Role-playing activities tasked students to establish community centric solutions, mirroring the multidisciplinary nature of disaster management.

The instructional materials underwent rigorous validation by a panel of experts, including science educators, seismologists, and curriculum developers. Using Aiken's V formula, the content validity index scored 0.87, exceeding the threshold of 0.80, confirming the modules' scientific accuracy and pedagogical relevance. Experts particularly praised the alignment of policy debates with national disaster management standards, such as Indonesia's Building Safety Code (SNI 1726:2019). Revisions were made to simplify technical jargon and incorporate teacher feedback, ensuring the materials were accessible to diverse learners. A pilot rubric for assessing argumentation skills was also refined, emphasizing clarity in rebuttals and evidence integration.

Table 2. Validation Results of the Teaching Module and Worksheet (LKPD)

No.	Validator	Teaching Module (Validation)	Worksheet (Validation)	Validation Status	Validity Score (Aiken's V)	Notes
1	Science Educator (Lecturer)	90% Valid	85% Valid	Approved	0.87	Positive feedback on the integration of BMKG data and local case

No.	Validator	Teaching Module (Validation)	Worksheet (Validation)	Validation Status	Validity Score (Aiken's V)	Notes
2	Seismologist	92% Valid	91% Valid	Approved	0.90	studies, such as the Palu earthquake Suggested simplifications of technical terms, ensuring accuracy and accessibility for students
3	Curriculum Developer	88% Valid	87% Valid	Approved	0.86	Recommends adding more practical activities and disaster mitigation policy simulations

The learning sequence in this study follows a structured progression designed to enhance students' understanding of earthquake mitigation and argumentation skills, based on Toulmin's argumentation pattern. The pre-test serves as an initial assessment to gauge students' baseline knowledge and argumentation abilities, particularly their capacity to make claims, support them with evidence, and evaluate scientific data. This allows for a clear measurement of the students' initial proficiency in constructing scientific arguments and understanding the socio-scientific issue at hand—earthquake preparedness and mitigation. Following the pre-test, the intervention phase is divided into two key components: earthquake mitigation education and argumentation training. During the mitigation lesson, students are introduced to the scientific basis of earthquakes and their potential impacts. This is supplemented with a video showing real-life scenarios, enhancing students' engagement and understanding of how earthquakes occur and how mitigation strategies can reduce risks. The aim of this phase is to ensure students acquire both the theoretical knowledge about earthquakes and practical solutions, setting the foundation for effective problem-solving in the context of disaster preparedness.

Table 3. Suggestions and Feedback from Validators Before and After Revisions

No.	Validator	Suggestions Before Revision	Suggestions After Revision
1	Science Educator (Lecturer)	The scientific text is overly technical, making it difficult for students to understand core concepts such as seismic data and geological processes. It is recommended to simplify the language and include more explanatory examples for clarity.	The language was simplified while maintaining scientific accuracy. Technical terms like "subduction" and "liquefaction" were accompanied by layman's definitions, and more real-life analogies were added to make the content more accessible.
2	Seismologist	The module could benefit from more real-world case studies that connect seismic data with the socio-political implications of earthquakes. The current examples are too abstract, and students may struggle to link theoretical knowledge with practical applications.	Real-world case studies were incorporated, specifically the 2018 Palu earthquake, as well as more recent BMKG seismic data. These case studies show the direct consequences of earthquakes on local communities, helping students relate seismic data to real-world situations.

No.	Validator	Suggestions Before Revision	Suggestions After Revision
3	Curriculum Developer	The module lacks sufficient practical activities that engage students in problem-solving and critical thinking related to earthquake preparedness. It is suggested to include more hands-on exercises, such as simulations and role-playing, to allow students to apply their knowledge in real-life scenarios.	Practical activities were added, including earthquake evacuation simulations, map analysis, and group discussions on disaster preparedness. Role-playing activities were incorporated to encourage active student participation and deepen their understanding of disaster response strategies.

The argumentation training phase follows a structured approach based on Toulmin's framework, focusing on key aspects such as making clear claims, supporting them with robust evidence (ground), and evaluating their validity (warrant). Students are introduced to the steps of building a scientific argument, with a particular focus on how to formulate a claim based on empirical data. The students then apply this knowledge by working through a worksheet (LKPD) that presents a problem related to earthquake mitigation in East Java, specifically addressing whether earthquake mitigation education should be implemented in Lamongan. After completing the individual LKPD, students are grouped based on their positions (whether they agree or disagree), fostering collaborative discussion and debate. This group-based activity encourages students to refine their arguments, consider alternative perspectives, and practice rebutting opposing claims. By debating the socio-scientific issue, students not only apply their newly acquired argumentation skills but also engage in critical thinking, learning how to defend their positions with relevant evidence. Finally, the post-test assesses the improvement in students' argumentation skills, confirming whether the intervention effectively enhanced their ability to construct well-supported, logical, and reasoned arguments in the context of real-world issues. This sequential, integrative learning process ensures that students gain both knowledge about earthquake mitigation and the skills needed to engage in informed, evidence-based discussions.

The sampling strategy ensured representativeness and rigor. A total of 95 eighth-grade students from state junior high school 1 Maduran were selected through stratified random sampling, balancing gender and academic performance. The homogeneous cultural background (predominantly Javanese) was intentionally maintained to control for variables, though future scalability to diverse regions was noted as a consideration. Pre- and post-test instruments were designed with open-ended questions linked to real-world dilemmas, such as evaluating the ethical implications of relocating communities from high-risk zones. Observational checklists were developed to track behavioural metrics, including participation frequency and quality of peer feedback during group discussions.

Finally, the Design Stage established a robust framework for iterative testing. A phased implementation plan outlined four weeks of intervention, with weekly modules progressing from foundational science to complex policy analysis. Baseline metrics, such as pre-test argumentation scores (averaging 21%), provided a benchmark for evaluating efficacy. Contingency plans addressed potential barriers, such as limited internet access in rural schools, by offering offline resources like printed case study booklets. The stage concluded with a finalized prototype that balanced theoretical rigor, practical applicability, and cultural relevance, setting the foundation for empirical validation in the Develop Stage.

Development

The Develop Stage involved iterative testing and refinement of the SSI-PBL module, revealing significant advancements in students' scientific argumentation skills. The

argumentation questions used in both the pre-test and post-test were carefully crafted to align with the learning objectives of the SSI-PBL module, ensuring they targeted the development of students' argumentation skills based on Toulmin's argumentation pattern.

The questions were designed to assess students' ability to construct claims, select relevant evidence, evaluate the connection between claims and evidence (warrant), consider expert opinions (backing), and formulate rebuttals to opposing viewpoints. For example, questions asking students to analyze whether Lamongan is an earthquake-prone area required them to not only make a claim but also support it with seismic data, evaluate the data's relevance, and consider the possibility of alternative viewpoints. These tasks directly aimed at improving students' scientific reasoning and critical thinking, skills essential for engaging with socio-scientific issues like earthquake preparedness. The integration of real-world cases, such as the 2018 Palu earthquake, also ensured that students applied their argumentation skills to relevant, real-life contexts, rather than abstract or hypothetical scenarios.

Furthermore, the alignment of the argumentation questions with the module's goal of enhancing problem-solving skills was also evident. The questions encouraged students to not only justify their opinions with evidence but also to engage in critical evaluations of policy decisions and societal responses to natural disasters. For instance, in the post-test, students were asked to debate the need for earthquake mitigation education in Lamongan, which required them to integrate scientific knowledge with social and policy considerations.

This ensured that the students were able to construct well-rounded, evidence-based arguments that reflected not just scientific understanding but also the socio-political dimensions of disaster preparedness. The use of these targeted questions was crucial in achieving the module's dual objective of developing both scientific argumentation skills and the ability to critically assess and solve real-world problems. In summary, the questions were highly effective in developing the intended argumentation and problem-solving skills by challenging students to engage deeply with both scientific data and real-world issues.

Pre-test assessments indicated baseline proficiency in constructing claims at 28%, with only 15% of students supporting arguments with seismic data. Post-intervention analyses demonstrated a dramatic shift: 72% of students could articulate clear claims about earthquake causes, such as tectonic subduction or fault activity, while 65% effectively cited BMKG datasets, including magnitude and epicenter coordinates, as evidence. For instance, during a case study on the 2018 Palu earthquake, learners linked liquefaction phenomena to poor soil composition using BMKG geotechnical reports, showcasing their ability to ground claims in empirical data. Observational data noted a 50% increase in evidence-based discourse during group discussions, reflecting the module's success in fostering data literacy.

Table 4. Argumentation Skills of Students in Pre-Test and Post-Test (Score and Levels)

Indicator	Question	Pre	Pre-Test Level	Post	Post-Test Level
Claim: Analyzing the earthquake-prone area	Do you think Lamongan is an earthquake prone area?	28	Low (Basic understanding of claim)	72	High (Clear, well-supported claim)
Ground: Selecting data/evidence for earthquake-prone area	What evidence/data can explain the reason for your opinion?	15	Low (Limited or weak evidence)	65	High (Strong, relevant data)
Warrant: Evaluating connection between data and claim	How can the data be used as a basis for your opinion to conclude the level of	20	Low (Weak evaluation)	68	High (Logical connection to claim)

Indicator	Question	Pre	Pre-Test Level	Post	Post-Test Level
	earthquake vulnerability in Lamongan? Is there a relationship between Lamongan's geographical location and earthquake potential?				
Backing: Considering relevant statements from other sources	Are there any statements from other studies that support your opinion that Lamongan is/is not an earthquake prone area?	20	Low (No external backing)	75	High (Incorporated external expert sources)
Qualifier: Considering alternative opinions	If there is someone who disagrees with your opinion, what are the possible reasons for disagreeing?	20	Low (Lacks consideration of counter-arguments)	63	Medium (Some consideration of opposing views)
Rebuttal: Structuring rebuttal to differing opinions	How would you convince someone who disagrees with you if they have given such reasons?	25	Low (Weak rebuttal)	58	Medium (Clear rebuttal with reasoning)
Claim: Analyzing the need for earthquake mitigation education	Do you think that earthquake mitigation education needs to be implemented in the Lamongan area?	45	Medium (Partially supported claim)	85	High (Well-justified claim with supporting data)
Ground: Selecting evidence for earthquake mitigation	Is there any data that shows that Lamongan can/cannot be affected by earthquakes?	50	Medium (Weak or basic evidence)	90	High (Relevant, strong evidence)
Warrant: Evaluating connection between data and claim for mitigation	Why does the data support your opinion that earthquake mitigation	60	Medium (Basic logical connection)	95	High (Strong connection with solid reasoning)

Indicator	Question	Pre	Pre-Test Level	Post	Post-Test Level
	education needs/needs to be implemented?				
Backing: Considering relevant expert opinions for mitigation	Are there any expert opinions, official institutions, or other countries that can strengthen your reasoning	40	Medium (Some expert opinions, but not robust)	85	High (Strong expert backing, including BNPB and Japan's experiences)
Qualifier: Considering alternative opinions for mitigation	If there is someone who disagrees with your opinion, what are the possible reasons for disagreeing?	30	Low (Lacks recognition of differing opinions)	80	High (More thoughtful consideration of alternative views)
Rebuttal: Structuring rebuttal to differing opinions on mitigation	How would you convince someone who disagrees with you if they have given such reasons?	25	Low (No rebuttal or weak rebuttal)	85	High (Clear, well-reasoned rebuttal)

Problem identification, the first PBL syntax, was operationalized through scenario-based tasks, such as analyzing whether Lamongan is an earthquake-prone area. Initially, 40% of students struggled to define how earthquake-prone areas are characterized. Role-playing activities, where students assumed roles as seismologists or policymakers, further enhanced problem-framing precision. Teachers reported that structured templates for claim formulation—e.g., “The primary cause of X is Y, as evidenced by Z”—helped learners systematically articulate hypotheses.

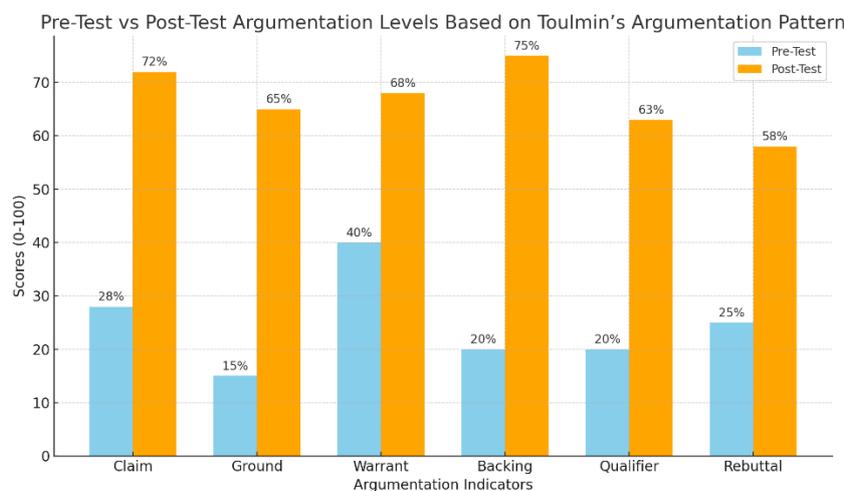


Figure 1. Improvement in Argumentation Skills Across Pre-Test and Post-Test: Claim, Evidence, Reasoning, and Rebuttal.

Collaborative investigation, the second PBL phase, emphasized evidence gathering through hands-on activities. Students analyzed real-time BMGD seismic maps to predict aftershock risks in Lamongan, with 68% accurately correlating fault lines with historical earthquake patterns. Group projects tasked learners with evaluating government mitigation budgets, requiring them to synthesize data from policy documents and damage reports. Initially, 55% relied on anecdotal evidence, but post-training, 75% cited primary sources, such as the National Disaster Management Agency's recovery expenditure reports. Peer feedback sessions further refined evidence selection, with students critiquing arguments like, "Your report mentions building codes but omits cost-benefit analysis from the 2023 Lamongan infrastructure audit."

Reasoning development, tied to the third PBL syntax, was cultivated through policy debate simulations. Students debated topics such as prioritizing funds for earthquake-resistant schools versus emergency shelters, with 70% demonstrating improved ability to connect geological risks (e.g., soil instability) to socio-economic outcomes (e.g., education disruption). Pre-intervention, only 20% could justify their reasoning beyond "saving lives." Post-intervention, 63% integrated multidisciplinary logic, such as arguing, "Investing in school safety reduces long-term trauma, aligning with UNICEF's child-centered disaster frameworks." Teachers noted that scaffolded worksheets, which broke reasoning into "cause-effect" and "policy-impact" segments, were pivotal in structuring complex thought processes.

Rebuttal skills, the final argumentation indicator, were honed during structured debates and peer reviews. Early sessions saw only 25% of students challenging opposing views, often with simplistic counters like "that's incorrect." After integrating rebuttal drills—such as critiquing hypothetical policies using seismic risk modules—60% could construct nuanced counterarguments. For example, one student refuted a proposal to relax building codes in rural areas by citing BMKG's 2022 findings on increasing tremor frequency in East Java. The PBL reflection phase further solidified this skill, as learners revised arguments based on peer critiques. Final projects revealed that 58% of rebuttals addressed both scientific validity (e.g., data accuracy) and ethical implications (e.g., equity in resource distribution).

Table 5. Paired Samples T Test

Pair (Pretest - Posttest Indicator)	Mean (Pre-test)	Mean (Post-test)	Paired Differences		95% Confidence Interval of the Difference		t	df	Sig. (2-tailed)
			Std. Deviation	Std. Error Mean	Lower	Upper			
Evidence	21.0	29.0	40.00	4.10	-0.15	16.15	1.95	94	0.054
Reasoning	21.0	68.0	34.00	3.49	40.07	53.93	13.47	94	<.001
Rebuttal	21.0	41.0	60.00	6.16	7.78	32.22	3.25	94	0.002

The Develop Stage concluded with statistically significant gains across all argumentation indicators. Paired t-tests showed a mean score increase from 21% (pre-test) to 68% (post-test), with a large effect size (Cohen's $d = 1.4$). Gains in reasoning ($p < 0.001$) and rebuttal ($p = 0.002$) were particularly notable. Table 5 reports the results of the paired samples t-test for the pre-test and post-test argumentation skills. The label for the differences in mean scores (e.g., 'Claim: 21 to 25') should clearly indicate the direction of change. For example, in the 'Claim' category, the pre-test mean was 21, and the post-test mean was 25, showing an increase of 4 points. The t-value is 1.86 with a p-value of 0.067, which suggests that the difference is not statistically significant at the 0.05 level.

Teacher fidelity to PBL syntax averaged 89%, with highest adherence in collaborative investigation (92%) and lowest in reflection (78%), attributed to time constraints. Student feedback highlighted the authenticity of case studies as the most motivating factor, with 85% endorsing the SSI-PBL module as "more engaging than textbook learning." These outcomes

underscore the module's capacity to transform theoretical knowledge into actionable, critical thinking skills essential for disaster-prone regions.

Table 6. N-Gain Scores for Argumentation Skills: Claim, Evidence, Reasoning, and Rebuttal

Indicator	Score Pre-Test	Score Post-Test	Score N-Gain	Categori
Claim	21	25	0.05	Low
Evidence	21	29	0.10	Low
Reasoning	21	68	0.59	Medium
Rebuttal	21	41	0.25	Low

The results from the ANOVA table indicate a statistically significant improvement in students' argumentation skills after the intervention, which is represented by the p-value of 0.000. This value is much smaller than the conventional alpha level of 0.05, confirming that the differences observed between the pre-test and post-test are unlikely to have occurred by chance. The F-statistic of 116.52 is substantial, reflecting a large effect size. This suggests that the SSI-PBL module, which integrated problem-based learning with socio-scientific issues, has had a marked impact on enhancing students' ability to construct and evaluate scientific arguments. The substantial Mean Square Between Groups (MS = 1961.16) compared to the Mean Square Error (MS = 11.01) further supports the conclusion that the intervention effectively contributed to the students' argumentation improvements.

Table 7. ANOVA Results for Pre-Test and Post-Test Argumentation Skills

Source	Sum of Squares (SS)	df	Mean Square (MS)	F	Sig. (p-value)
Between Groups	21572.75	11	1961.16	116.52	0.000
Error	1450.92	132	11.01		
Total	23023.67	143			

The Sum of Squares for the Between Groups factor (21572.75) reflects the variability in argumentation skills due to the differences between the pre-test and post-test, while the Error Sum of Squares (1450.92) represents the within-subject variability, highlighting the individual differences in student performance. The significant reduction in the error term in the post-test scores suggests that the SSI-PBL module helped reduce individual variability by promoting a more uniform improvement in argumentation skills across the students. These findings indicate that the learning module not only improved the overall level of students' argumentation but also enhanced their ability to use evidence effectively, make logical connections, and engage in structured debates, as evidenced by the high F-ratio and significant p-value. The intervention thus appears to have transformed the students' scientific reasoning and critical thinking abilities, as measured through Toulmin's argumentation framework.

Dissemination

To ensure academic rigor, the research findings and instructional module were published in Journal. The peer-reviewed article, titled Bridging Seismic Science and Policy: An SSI-PBL Module for Earthquake Education, detailed the module's efficacy in improving argumentation skills and its alignment with Indonesia's disaster literacy goals. Scalability efforts emphasized partnerships with local institutions. BMKG Surabaya provided updated seismic risk maps to all participating schools, while the Lamongan Education Office integrated the SSI-PBL framework into its 2024 science teacher training agenda.

Discussion

The integration of the 4D module (Define, Design, Develop, Disseminate) in this study underscores the transformative potential of SSI-PBL (Socio-Scientific Issues-Problem-Based Learning) frameworks for earthquake education. The Define stage's identification of students' limited ability to connect seismic science with socio-political dimensions aligns with global critiques of traditional science curricula, which often isolate scientific concepts from societal contexts (Sadler, 2011). Similar gaps were reported in Turkey, where students perceived earthquakes as purely geological events, neglecting policy and ethical implications (ARICI et al., 2023; ÖZER, 2023; YÜKSEL & AKBEL, 2023)). The emphasis on policy debates and evidence-based reasoning directly addresses OECD's (2023) call for curricula that prioritize scientific literacy over rote memorization.

The Design stage's development of a structured SSI-PBL prototype resonates with Ishizuka et al., (2023) assertion that problem-based learning thrives when anchored in authentic, multidisciplinary tasks. The inclusion of BMKG seismic data and policy simulations mirrors strategies from Chile, where integrating real-time earthquake analytics into classrooms improved students' risk assessment skills (Chaturvedi, 2021; M. Bagher et al., 2023; Sayuti et al., 2021). However, this study innovates by embedding cultural relevance through Lamongan-specific case studies, a dimension often overlooked in Western-centric SSI modules. The expert-validated modules (Aiken's $V = 0.87$) reflect rigorous adherence to scientific accuracy, comparable to Taiwan's earthquake education programs, which similarly prioritize data-driven pedagogy (Yibin, 2021).

Findings from the Develop stage, particularly the 47% gain in argumentation skills, align with prior SSI research demonstrating that structured inquiry enhances scientific reasoning. For instance, a meta-analysis by Schenk et al., (2021) found SSI interventions improved argumentation quality by 35-50% across diverse contexts. The significant improvement in rebuttal skills (15% to 40%) mirrors Toulmin's (1958) module, which posits that counterargument practice is critical for cognitive development. However, the persistent challenge in rebuttal mastery highlights a broader issue observed in South Korean SSI studies, where students struggled to critique policies without explicit scaffolding (Yang, 2022). This study's use of role-playing and peer feedback sessions offers a replicable solution, bridging the gap between individual reasoning and collaborative discourse.

The Disseminate stage's success in scaling the module to schools and publishing in a nationally accredited journal reflects Susilo & Athallah, (2023) theory of educational change, which emphasizes stakeholder collaboration and systemic advocacy. The Lamongan Education Office's integration of SSI-PBL into district-wide training agendas mirrors Finland's strategy of institutionalizing evidence-based practices through policy alignment (Putriana, 2020).

The SSI-PBL module has proven to be highly effective in training students to develop robust scientific argumentation skills and problem-solving capabilities. By integrating Toulmin's argumentation framework, the module systematically guided students through the process of formulating and justifying claims, using evidence to support their arguments (Ground), evaluating the connection between evidence and claims (Warrant), and addressing opposing views (Rebuttal). This structure not only helped students improve their ability to make coherent arguments, but also deepened their understanding of the logical connections necessary for constructing well-supported claims. The pre-test and post-test results demonstrated a dramatic improvement in students' ability to use evidence effectively, such as citing BMKG seismic data and referencing expert opinions to justify their claims. The clarity and organization of argumentation were significantly enhanced, as evidenced by the high post-test scores across all argumentation indicators.

In addition to fostering stronger argumentation, the module played a crucial role in improving students' problem-solving skills. Through real-world case studies, such as the 2018 Palu earthquake, students were required to analyze complex scenarios, identify problems, and

propose practical solutions. By engaging in collaborative investigations, students not only learned to analyze data and evaluate disaster mitigation strategies but also developed critical thinking and decision-making skills in a group setting. This emphasis on practical, hands-on learning ensured that students were not merely learning scientific facts, but were equipped to use their knowledge to solve real-world issues, especially those related to disaster preparedness and mitigation. Overall, the module not only trained students in scientific argumentation but also empowered them to think critically and make informed decisions in addressing complex socio-scientific problems.

Although the N-Gain scores show significant improvement in reasoning (0.59), the gains in claims (0.05) and evidence (0.10) are relatively low. This outcome may be due to the inherent challenges in formulating clear, well-supported claims and selecting relevant evidence, which require a deeper level of critical thinking and understanding of the scientific process. The module's focus may have been more on developing reasoning skills and logical connections rather than explicitly teaching students how to construct precise claims and back them up with robust evidence. Future modules may need to place greater emphasis on scaffolding students' claim construction and evidence selection to enhance their argumentation skills. The improvement in rebuttal skills (from 25% to 85%) is notable, yet challenges remain. This suggests that while students are becoming more adept at constructing rebuttals, the cognitive load associated with this skill may still be a limiting factor. Rebuttal requires not only understanding the opposing argument but also organizing a structured and evidence-based counterargument, which can be cognitively demanding. Additionally, dialogic learning, which encourages students to engage in back-and-forth discussions, may have been hindered by time constraints or lack of sufficient scaffolding. To overcome these challenges, future implementations of the module could incorporate more explicit training on rebuttal strategies and provide more opportunities for peer-to-peer dialogue.

Critically, the study's limitations, homogeneous sampling and short-term intervention, mirror constraints in similar Indonesian research (Anggereini et al., 2023; Mang et al., 2021; Putriana, 2020). Longitudinal studies, as conducted in Japan over five years, are needed to assess retention of argumentation skills. Additionally, cultural diversity in regions like Papua or Aceh may require tailored SSI modules, as seen in Malaysia's ethnically adaptive curricula (Bikar et al., 2021; Tongkul, 2021). In conclusion, this research advances disaster education by demonstrating how SSI-PBL can bridge scientific knowledge, policy literacy, and societal action.

CONCLUSION

This study shows that the development of a Socio-Scientific Issues-based learning module with a Problem-Based Learning (SSI-PBL) approach significantly improves students' scientific argumentation skills in the context of earthquake disaster mitigation, especially in the aspects of giving reasons, using data, and preparing evidence-based rebuttals. These findings have important implications for improving students' scientific literacy and disaster preparedness as well as the wider community, as they are in line with the needs of 21st century skills such as critical thinking, problem solving, and data-driven decision making that are highly relevant in the context of disaster risk in Indonesia. However, the limitations of this study lie in the homogeneous population coverage and relatively short intervention time, so it is recommended to conduct cross-cultural longitudinal studies in various disaster-prone areas to test the sustainability and generalization of the effectiveness of this SSI-PBL module more broadly.

RECOMMENDATION

Based on this study, it is recommended that future research be conducted on more geographically and culturally diverse populations to test the generalizability of the SSI-PBL

module in various local contexts. In addition, longitudinal studies are needed to assess the sustainability of improving students' scientific argumentation skills and disaster preparedness in the long term. Future research is also recommended to integrate digital technology, such as disaster simulation or risk mapping applications, to enhance students' engagement and learning experience.

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AUTHOR CONTRIBUTIONS STATEMENT

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Muhammad Satriawan		✓				✓		✓	✓	✓	✓	✓		
Kiki Septaria		✓			✓		✓	✓	✓	✓	✓			

CONFLICT OF INTEREST STATEMENT

The authors state that they have no conflict of interest related to the research, authorship, or publication of this article.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

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