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Research Article

Enhancing students' argumentation skills through socio-scientific real-world inquiry: A quasi-experimental study in biological education

Anwari Adi Nugroho[1], Sajidan Sajidan[2], Suranto Suranto[3] and Mohammad Masykuri[4]

[1]*Doctorate Program of Natural Science Education, Universitas Sebelas Maret & Biology Education Departement, Universitas Veteran Bangun Nusantara, Indonesia (ORCID: 0000-0003-0950-5286)*
[2]*Doctorate Program of Natural Science Education, Universitas Sebelas Maret, Indonesia (ORCID: 0000-0001-6306-6849)*
[3]*Doctorate Program of Natural Science Education, Universitas Sebelas Maret, Indonesia (ORCID: 0000-0003-4313-8627)*
[4]*Doctorate Program of Natural Science Education, Universitas Sebelas Maret, Indonesia (ORCID: 0000-0003-3342-0485)*

Argumentation skills are important for students to analyze and evaluate critical information, especially in complex science issues. Socio-Scientific Real-world Inquiry [SSRI] learning helps students develop deep scientific understanding and the ability to build evidence-based arguments in a real context. This study aimed to examine the effectiveness of SSRI learning model in improving argumentation skills. The research design used was quasi-experimental with a pretest-posttest non-equivalent control group design, in which argumentation skills were measured before and after the intervention in two groups: an experimental group consisting of 44 students who received learning with the SSRI model and a control group comprised of 46 students who followed the inquiry learning. Analysis of changes in pretest and posttest scores on each aspect of argumentation skills was conducted using a paired sample t-test. In contrast, comparison of posttest scores between the two groups was analyzed by independent sample t-test. Analysis of the effect size on each aspect of argumentation skills in the control group and experimental group using Cohen's Effect Size method. The analysis results showed that the SSRI learning model was more effective in improving argumentation skills than the inquiry learning. These results indicate that SSRI can be an effective learning approach for educators and educational policymakers in an effort to develop argumentation skills that are crucial for individuals.

Keywords: Argumentation; Biology education; Experimental study; Inquiry learning; Socio-scientific issues

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1. Introduction

Twenty-first-century learning requires students to have essential life skills in solving real-world problems, including argumentation skills as a basis for decision-making (OECD, 2019). Argumentation skills are crucial in learning science, especially biology, because they play a role in developing scientific knowledge (Arslan et al., 2023; Ping et al., 2020), participating in scientific argumentation (Osborne et al., 2016), supporting understanding of science concepts (Choden & Kijkuakul, 2020; Pekel, 2021), and sharpening scientific thinking skills through group discussions (Krell et al., 2024; Majidi et al., 2021; Memiş & Çevik, 2018). Argumentation in science learning

Address of Corresponding Author

Sajidan Sajidan, PhD, Natural Science Education, Ir.Sutami Street, Number 36, Kentingan, Jebres, Surakarta, Central Java. Indonesia.

sajidan@fkip.uns.ac.id

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requires strong evidence, logical reasoning, and persuasive techniques to strengthen claims and build constructive discussions.

Science learning with argumentation encourages students to actively engage in the process of constructing, evaluating and communicating arguments supported by logical reasoning and in-depth scientific concepts and practices (Alfarraj et al., 2023; Mesci et al., 2023). Through this approach, students not only learn to express their views in a structured manner but also develop the ability to critically assess the strengths and weaknesses of arguments (Demircioglu et al., 2023). If students can express their arguments accompanied by scientific evidence and reasoning, they will likely develop an understanding of scientific principles and phenomena. Previous research conducted on argumentation in the classroom shows that learning with argumentation can improve these skills. However, research limitations were found in the testing schemes and elements, which were subjective, and there were differences between the evaluators in identifying these elements. Argumentation activities in the classroom are carried out not only through direct assessment but also through face-to-face meetings or group discussions (Jho & Ha, 2024). In science classes, teacher and student questions have a contributing role in initiating and developing arguments. Research has shown that teachers usually ask students closed questions so that students cannot think at a phenomenal level of knowledge. In classroom learning, open questions are needed to start the argumentation process (Erdogan et al., 2017; Sulistina et al., 2024). In the argumentation process, students assume that science is a process of expressing and developing their thoughts continuously (Hidayati et al., 2023).

Argumentation skills are important for students in learning biology, so learning innovations are needed to improve argumentation skills (Lestari et al., 2024; Nugroho et al., 2023). A study of student arguments showed that the aspects of claim, evidence, backing, and qualifiers were categorized as moderate, while warrant and rebuttal were categorized as poor. The failure to develop argumentation properly in learning causes the argumentation to be poor. One solution for developing arguments is to design innovative inquiry learning (Nugroho et al., 2023). Learning biology has the potential to enhance argumentation skills through the implementation of learning models. Learning biology with questioning activities makes students active in identifying problems, collecting evidence, and explaining evidence so that they can develop argumentation skills (Chin & Osborne, 2010; Lestari et al., 2024). Students practice asking questions and using scientific evidence to support their answers (Wenning, 2011a), thereby developing their argumentation skills. Research results show that a learning model that is oriented towards questions and investigations, such as an inquiry model, can have a positive impact on the understanding of a subject and can improve argumentation skills (Ping et al., 2020; Probosari et al., 2022; Vácha & Rokos, 2017).

1.1. The Relationships among Argumentation, Inquiry, Socio-scientific Issues in Real-world Contexts

Inquiry learning has been widely applied in biology education to improve students' argumentation skills. Compared to ordinary learning, inquiry learning is better at improving argumentation (Antonio & Prudente, 2021; Lunn Brownlee & Ryan, 2020; Songsil et al., 2019). The use of inquiry models that emphasize arguments has been shown to improve the quality of student argumentation compared to traditional approaches. With inquiry, students can actively explore problems, gather evidence, and construct data-based arguments (Putri et al., 2024). For example, at the evidence-gathering activity of this learning process, students are directed to collect data through experimentation, observation, or literature review. Furthermore, at the data analysis and inference activity, students are invited to critically evaluate their findings, using the data to support claims made or to refute other arguments. With this structured approach, students are taught to build arguments based on valid scientific data rather than simply relying on personal opinions or assumptions. Developed argumentation skills not only help students logically defend views in discussions, but also encourage more in-depth problem solving, which directly impacts positively on academic outcomes. Thus, this approach is not only relevant in the development of critical thinking skills, but also has a significant impact on students' academic achievement (Eshetu et al., 2022; Koçoğlu & Kanadlı, 2024; Öztürk et al., 2022). The real-world application learning model is one level of inquiry that can develop students' argumentation skills in biology learning. This approach involves students analyzing biological phenomena, collecting evidence, and building logical reasoning. through this learning model, students can conduct independent investigations with teacher guidance, allowing them to explore biological phenomena that reflect real-world issues (Wenning, 2011b, 2011a). These activities not only support students in linking biology concepts to real-life situations but also strengthen their ability to construct evidence-based arguments through direct engagement with real problems.

However, several previous studies have shown that learning with inquiry has challenges and negative results and is less convincing, so its effectiveness is questionable (Capps & Crawford, 2013; Nicol, 2021; Yoon et al., 2012). A review of the literature shows that lecturers often experience major difficulties that cause concerns about the effectiveness of implementing this method, especially in terms of the need for dynamic classroom management, flexible teaching approaches, active interaction between lecturers and students, and professional support for teachers (Dah et al., 2024). Another challenge was ensuring that the problems presented truly reflect authentic situations in the field. This challenge arises because authentic situations require complex and contextualized issues for students to experience direct relevance to the real world. So that learning outcomes can be achieved optimally, biology materials must describe situations that actually occur in the field, improving students' analytical and argumentation skills in depth (Prahani et al., 2021). In addition, the dominance of the teacher's role in the learning process is often a significant obstacle in the development of students' independent investigation skills. When teachers take over too much of the learning process, students tend to become passive learners who only wait for instructions and answers from the teacher, thus inhibiting the development of their investigative skills. This is contrary to the essence of inquiry learning, which emphasizes students' activeness in constructing their knowledge. Secondly, the relatively long learning duration can have a negative impact on the level of student engagement. Too long a learning period has the potential to cause boredom, lower concentration levels, and reduce students' enthusiasm in actively participating during the learning process (Gormally et al., 2016; Khalaf & Zin, 2018). One of the main obstacles is the gap between the difficulty of the problems presented and students' understanding, which often hinders their ability to process information and argue. Research shows that students' motivation and engagement increase when they are given the opportunity to explore interesting topics that are relevant and meaningful to them (Subiantoro et al., 2021; Zeidler et al., 2019).

The relevance model is the most well-known (Stuckey et al., 2013). It emphasizes that connecting scientific ideas with students' daily experiences is essential to increase their interest and desire to learn. In addition, general knowledge construction models focus on conceptual understanding through question-based learning, but they have limitations. For example, relevance models are often too general and do not pay enough attention to controversial aspects that are important for building argumentation skills. However, the general knowledge construction model such as inquiry learning usually ignores the social context and community issues that can increase student participation. Effective science learning must be able to connect with students' life experiences and relevant issues that develop in society. Irrelevant or unfamiliar problems often make students less interested in identifying and discussing them. As a result, despite the focus on argumentation skills, some students still need help in developing their analytical and argumentation skills in biology. Therefore, it is important to tailor biology materials to be more relevant to the context and students' level of understanding, which can help improve science-based learning and optimization of argumentation skills (Çalık & Wiyarsi, 2021; Effendi-Hasibuan et al., 2020).

Socio-scientific issues [SSI]-based approaches that are relevant to students' real-life contexts have been shown to increase students' motivation and engagement in learning (Cents-Boonstra et al., 2021). SSI cover complex, context-based and often controversial issues that spark debate in society as social, political and scientific perspectives influence them. These topics are interesting to study because they motivate students through in-depth discussions that involve assessing information from multiple points of view. By facing real problems that require critical analysis, students are not only trained to evaluate evidence and arguments but also develop argumentation and decision-making skills that are relevant to their lives (Abrami et al., 2015; Eastwood et al., 2012; Goodenough et al., 2023; Wansink et al., 2023; Zeidler et al., 2019). SSI are also often controversial due to the different values, views and interests of the parties involved. For example, on the issue of genetic engineering, there is a debate on the benefits of the technology compared to the ethical and safety risks it poses (Christenson & Walan, 2023; Saad et al., 2017). Increased interest in SSI has opened up new opportunities in the development of learning that is oriented towards improving students' argumentation skills (Falah et al., 2024). Integrating socio-scientific issues can provide relevant learning experiences while motivating students to argue and take a stand based on scientific evidence (Nurtamara et al., 2019; Subiantoro et al., 2021; Zeidler et al., 2019).

The implementation of socio-scientific issues in education can increase students' awareness of social and ethical responsibilities in scientific decision-making (Fang et al., 2019; Garrecht et al., 2020; Mun et al., 2022). This approach encourages students to think holistically and consider various aspects, including the long-term impact on society and the environment. Through discussions involving diverse perspectives, students are trained to develop argumentation skills and deepen their understanding of issues that affect their daily lives (Dawson & Venville, 2022; Sparks et al., 2022). Thus, the socio-scientific issue-based approach in biology learning not only prepares students to be competent scientists but also responsible citizens, sensitive to complex global issues, and able to evaluate arguments and express opinions clearly and persuasively.

The implementation of SSI in science learning in Indonesia still needs to be improved and requires improvement (Genisa et al., 2020). A literature review showed the importance of further exploration in the area of SSI to support the development of more effective pedagogies in science education (Falah et al., 2024). While previous research has shown that inquiry approaches can support the development of argumentation skills, most studies have yet to specifically detail the contribution of SSI within an inquiry learning framework. Various real-world-based learning models have been developed, some with the integration of argumentation components in the syntax of inquiry, but generally have yet to integrate SSI (Nurohman et al., 2021). Research on argumentation in science learning generally aims to examine the impact of argumentation after the application of argumentation-based learning (Aldresti et al., 2018; Aslan, 2019; Cetin, 2014). Meanwhile, inquiry learning (at the level of discovery learning, inquiry lessons) with socio-science issues has been conducted with the aim of improving thinking skills (Aldresti et al., 2018). In fact, the integration of SSI can add a relevant and engaging contextual dimension, enrich classroom discussions and debates, and prepare students to face complex real-world challenges. The inquiry approach applied in the classroom is often generalized and lacks highlighting real-life controversial contexts that are important for developing students' readiness to face global challenges. Therefore, more in-depth research is needed to assess how the effectiveness of a learning model that combines inquiry with SSI can improve students' argumentation skills, specifically in biological education.

The increasing complexity of global issues, such as genetic engineering in modern biotechnology, demands a transformative approach to science education. Various research results support that the implementation of inquiry learning integrated with socio-scientific issues (SSI) is effective in training and developing students' ability to argue. Inquiry is an important element in biology education and needs to be trained to students, especially for those who will become teachers in the future. Trends in the application of inquiry are reflected in several literature reviews which conclude that much more research is needed on the epistemic aspects of inquiry in science education (Dah et al., 2024; Dimopoulou & Gasparatou, 2024).

Various learning models have been developed to connect science concepts with real life. Context-Based Learning [CBL] and Science-Technology-Society-Environment [STSE] learning cycle are two approaches that are widely used because they emphasize the relevance of scientific concepts in the context of the real world. CBL aims to improve students' understanding by linking learning materials with everyday experiences. Despite its aim to link scientific concepts with real-world experiences, a review study reported that context-based learning can be perceived as detached from social and real-world contexts, ultimately reducing students' sense of relevance and interest in science (Ültay & Çalık, 2012). Additionally, this model does not directly emphasize developing structured argumentation skills or critical engagement in complex socio-scientific issues (Aikenhead, 2006; Ummels et al., 2015). Meanwhile, the STSE learning cycle encourages exploration of the connections between science, technology, society, and the environment (Bennett et al., 2003; Lubben, et al., 2005). This approach emphasizes the relevance of science to social issues and their applications over traditional approaches that often concentrate on theoretical and abstract concepts that may not connect with students' real-life experiences (Sanger & Greenbowe, 1996). However, this model often lacks a structured inquiry component, which can result in suboptimal development of critical thinking skills and evidence-based argumentation (Calado et al., 2018). Both context-based and Science-Technology-Society approaches also risk overemphasizing the context, potentially obscuring core scientific principles and hindering students' overall scientific literacy (Bennett et al., 2003).

Socioscientific Issues differ from Science, Technology, and Society in terms of focus and educational approach. SSI emphasizes empowering students to connect scientific issues with moral and ethical principles in their lives, while also encouraging critical discussion to develop argumentation skills. On the other hand, Science-Technology-Society tends to focus more on the social context of science without emphasizing moral development and argumentation skills (Zeidler et al., 2005). While CBL and STSE contribute to contextualizing science learning, they do not fully integrate structured inquiry within socio-scientific issues a crucial aspect in strengthening scientific argumentation and decision-making. Argumentation is crucial for shaping individuals' understanding and decision-making regarding socioscientific issues, making its integration into educational practices essential. Effective evaluation of information is fundamental in dealing with SSI, as it directly influences the quality of reasoning and decision-making. Therefore, promoting argumentation skills within SSI contexts is vital for developing scientific literacy (Sadler, 2004). In contrast, the Socio-Scientific Real-World Inquiry model emphasizes structured inquiry as an integral part of the learning process. This structured approach is vital because SSIs are inherently complex and require students to systematically investigate problems, analyze evidence, and develop sound arguments. By guiding students through a clear sequence of inquiry steps, the SSRI model helps them navigate the intricacies of socio-scientific issues while building robust argumentation skills. Thus, SSRI provides a more systematic strategy that not only engages students in real-world issues but also equips them with the skills needed to construct well-reasoned, evidence-based arguments.

The SSRI model has key advantages over other science learning models. This approach focuses on developing argumentation skills through the exploration of socially and contextually relevant controversial issues. In addition, fostering scientific habits through the SSRI model contributes to building scientific attitudes that encourage critical thinking and responsible engagement with scientific information and socio-scientific issues. Scientific habits such as curiosity and rationality also enhance student involvement in debates and discourse, promoting active participation in discussions and decision-making processes (Çalik & Coll, 2012). The SSRI learning model not only connects theoretical knowledge with practical application but also hones students' ability to analyze issues, construct logical arguments, and make informed decisions in complex social and scientific contexts. Research shows that integrating SSI in inquiry learning not only helps students understand complex contemporary science issues but also prepares them to face real-world challenges (Gutierez, 2015; Suwono et al., 2023). Martini et al. (2021) found that the application of inquiry in the context of SSI can improve argumentation skills in students in the field of science education. In addition, research by Gul and Akcay (2020) showed that an SSI-based approach can develop critical thinking, openness, and confidence in reasoning and argumentation, especially for prospective science teachers. These findings indicate that SSI not only enriches students' analytical and critical abilities but also equips them with solid argumentation skills in dealing with complex and controversial issues in everyday life.

1.2. The Rationale and Significance of the Study

The application of the SSRI learning model are needed to improve the skills of prospective biology teachers in dealing with complex issues. When students engage in SSI-based discussions, they are encouraged to develop strong arguments, consider multiple viewpoints, and integrate scientific knowledge with social and ethical implications. Combining inquiry and SSI gives students a more meaningful and holistic learning experience. This process can enhance the argumentation skills needed to face global challenges. The inquiry approach combined with socio-scientific issues aims to equip them with important skills, especially in argumentation, which are needed to solve real-world problems. Through this learning, students are trained to be active, have a deep understanding, and be committed to solving complex problems. The SSRI approach also emphasizes the importance of integrating moral, ethical, and social aspects in biology learning so that students can evaluate the impact of their choices and actions on the environment and surrounding communities. Exploration of socio-science issues encourages students to develop data-based argumentation, expand global understanding, and build awareness to act responsibly within the local scope (Amos & Levinson, 2019). In addition, this approach has been shown to be effective in improving students' understanding of the long-term impact of individual and collective choices on societal well-being and environmental sustainability (Zeidler et al., 2019).

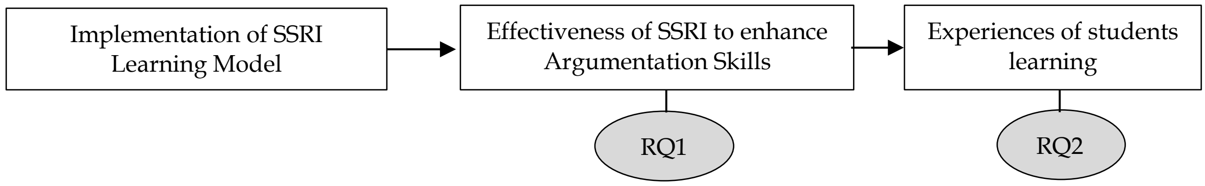
This study introduces an innovative learning model called Socio-Scientific Real-world Inquiry, a new approach in biology education that aims to develop students' argumentation skills through a real-world context that is rarely applied. Although there are many studies related to inquiry learning in biology, the effectiveness of inquiry supplemented with SSRI in the context of Genetically Modified Organisms [GMO] issues and its impact on improving students' argumentation skills still requires further exploration. For this reason, an appropriate methodology with strict control is needed to test the effectiveness of this model. In addition, this study uses a more in-depth analysis by measuring the effect size in each aspect of problem-solving skills, providing stronger empirical evidence of the effectiveness of SSI than the inquiry learning model. Thus, this study makes an important contribution to the educational literature as a basis for developing more effective SSI-based models, as well as encouraging educators and policymakers to consider the SSRI approach as an innovation in improving argumentation skills, especially for students majoring in Biology Education. It also raises important questions about the effectiveness of this approach in various other learning contexts. Through this study, the following essential research questions were proposed: 1) How does the effect of the SSRI learning model on students' argumentation skills, compared to inquiry learning? 2) What are the experiences of students using the SSRI learning model?

2. Method

2.1. Research Design

An overview of the procedure flow can be seen in Figure 1.

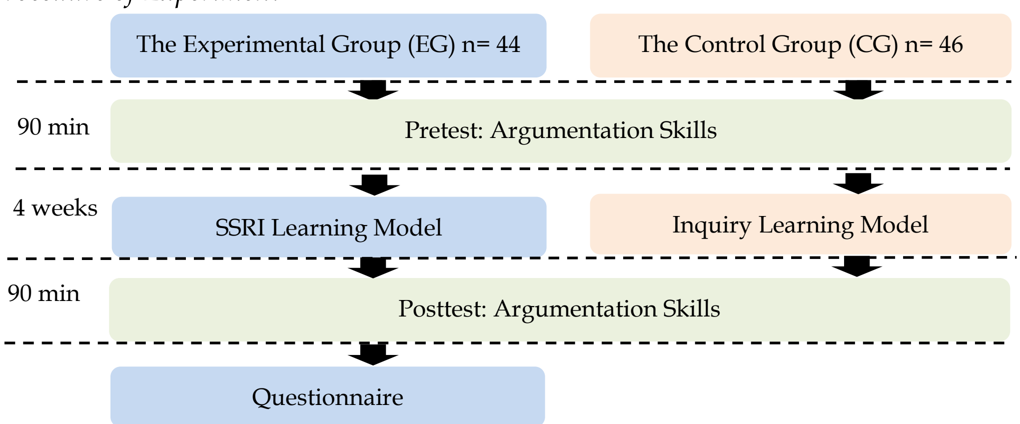
Figure 1
Research procedure based on the research questions (RQ)



This study used a quasi-experimental pretest-posttest non-equivalent control group design, where measurements were taken before and after the intervention in two groups: one group received the treatment. At the same time, the other group served as the control. Before the learning activities began, a pretest was given to measure students' initial skills. After the learning implementation, a posttest was conducted to evaluate the improvement of students' argumentation skills (Figure 2). This experimental study was carried out as part of a biotechnology course with a credit load of 2 semester credit system. The experimental process was implemented for four weeks includes a total of four meetings during the odd semester of the 2023-2024 academic year. Each meeting was designed based on the standard semester credit system in Indonesia, with the following details: 1) In-class activities: 100 minutes dedicated to discussions and classroom learning activities; 2) Structured assignments: 120 minutes for completing tasks; and 3) Independent activities: 120 minutes for individual exploration of materials and literature. To ensure the effectiveness of the self-directed activities, students in the experimental and control groups were asked to submit self-directed worksheets and participate in follow-up discussions during class. These steps helped monitor and evaluate their engagement in the self-study, ensuring alignment with the study objectives. While the intervention design included both in-class and out-of-class activities, the primary focus was on in-class activities, as these were directly observable and controllable by the instructor. Independent activities were considered complementary, providing additional opportunities for students to enhance their understanding and argumentation skills. This results in a total weekly workload of 340 minutes, adhering to Indonesia's national higher education standards. Thus, the implementation process adheres to national standards and aligns with pedagogical principles, ensuring sufficient time and workload to enhance students' argumentation skills effectively.

The independent variable in this study is the Socio-Scientific Real-world Inquiry learning model applied to the experimental group [EG], which addresses the topic of transgenic biotechnology, as well as the application of inquiry learning in the control group [CG]. Meanwhile, the dependent variable was students' argumentation skills, measured through tests (open-ended questions) before and after the intervention. This duration aligns with previous research and meta-analyses, which suggest that four weeks of structured implementation are sufficient to observe measurable improvements in argumentation skills (Çalik & Wiyarsi, 2024; Sugrah et al., 2023). Each group involved in this study received treatment in classes with the same lecturer and uniform classroom environment, so the difference in results between the experimental and control groups is expected to be influenced more by the treatment given than other external factors.

Figure 2
Procedure of Experiment



This study involved a population of 119 students of the Biology Education study program class at Muhammadiyah University of Surakarta, Central Java, Indonesia. The sample was selected using the purposive sampling method, taking into account relevant criteria to achieve the research objectives. This purposive sampling selection allows researchers to select samples selectively based on characteristics that are in accordance with the phenomenon under study so as to obtain significant information. The research sample consisted of 44 students (experimental group) and 46 students (control group). The experimental group was treated with the SSRI learning model, while the control group followed inquiry learning as a comparison. Students who participated in this study were eligible and willing to participate with the guarantee of confidentiality of their identity. The participants of this study, namely Biology Education students class, have similar demographic conditions. They are between 18 and 20 years old on average, with relatively similar socio-cultural backgrounds, namely coming from the Central Java region, Indonesia. Thus, the research subjects have fairly uniform characteristics, including age, grade level, and socio-cultural background. The total research subjects were 90 students, who were randomly selected based on their similar demographic conditions.

2.2. Procedures

2.2.1. Control groups

The control group in this study was carefully selected to ensure the validity of the quasi-experimental method. The control group was selected based on characteristics similar to those of the experimental group, including demographic factors, background, age, and other variables related to the study (Miller et al., 2020). The treatment given to the control group was inquiry learning, which is commonly used in biology classes. The inquiry learning model is an inquiry learning approach that is implemented without integrating socio-scientific issues in the learning process. Instead, it uses ordinary contextual problems that are more general and not directly related to social or controversial issues. An ordinary contextual problem used in this model, for example, is an issue associated with GMO crops, which focuses more on technical and scientific aspects without linking it to broader social, ethical, or controversial dimensions. This inquiry learning involves the stages of 1) observation; 2) manipulation; 3) generalization; 4) verification; 5) application (Wenning, 2011b). Details of the learning steps of the inquiry learning model are presented in Table 1.

Table 1
Phase of inquiry learning model

Phases	*Learning Activity*
Problem orientation	a. Observation of phenomena/issue that interest students. b. Students identify the phenomena/issue and find analogies and other examples of the phenomenon. c. Students create a question worth investigating.
Manipulation	a. Students discuss and debate emerging ideas for investigating the phenomenon/issue and develop approaches to analyzing it. b. Students create an investigation plan and carry it out to obtain qualitative and quantitative data.
Generalization	a. Students explain principles, laws, or theories relevant to the phenomenon/issue being studied. b. Students construct a logical and understandable explanation of the phenomenon/issue.
Verification	Students make predictions and prove them using general theories/principles developed in the previous stage.
Application	a. Students independently conclude and communicate with other students. b. The conclusions are mutually agreed upon and then applied to different situations as needed.

2.2.2. Experimental Groups

The experimental group applied inquiry integrated with socio-scientific issues in a real-world context, while the control group only used a inquiry learning model without additional SSI integration. The experimental group used the SSRI learning model, which excels in utilizing socio-scientific issues as the main problem to encourage students to argue. The SSI issue used in this study is GMO crops, which covers scientific, social, and ethical aspects. Thus, students can explore various perspectives in the discussion. The selection of the experimental group in this study is an important step that is done by considering the characteristics of the participants to achieve the research objectives (Creswell & Creswell, 2018; Fraenkel et al., 2012). The selection is based on the similarity of characteristics between the experimental and control groups, ensuring the results obtained are more accurate as an effect of the applied learning model intervention (Balkin & Lenz, 2021; Reichardt, 2019). With the similarity of these characteristics, bias can be minimized, and the internal validity of the research becomes more assured.

The SSRI learning model applied in this experimental group integrates the real-world application approach (Wenning, 2011b) with the socio-science issue-based learning method or SSI (Sadler, 2011). This integration resulted in the main components of the SSRI model, namely (1) learning syntax in 5 phases, (2) social systems that support interaction, (3) reaction principles to encourage active engagement, (4) support systems as learning aids, and (5) instructional and nurturant impacts (Joyce et al., 2015). The phase and sub phase of the SSRI learning model are a systematically designed framework to guide students in solving scientific social problems, starting from problem orientation to reflection. Phases are the main stages in learning designed to achieve objectives, while sub-phases are the detailed steps within each phase that help students go through the learning process systematically. Details of the phases and sub-phases of the SSRI learning model are presented in Table 2.

Table 2
Phases and sub phases of SSRI learning model

Phases and sub-phases	*Learning Activity*
Problem orientation	
Identification	The provision of SSI that is currently developing in society is related to learning material in the form of discourse/ readings or other forms.
	Students identify problems in the discourse/ SSI reading.
Main Topic Formulation	Students determine the main topic of the problem (pros and cons in SSI).
Manipulation	
Exploration	Students provide opinions regarding the main topics (pros and cons of SSI) found
Data Interpretation	Students provide explanations accompanied by scientific evidence to strengthen their opinions.
Generalization	
Explanation/ Experimentation	Students explain theoretically the topic of SSI problems to strengthen their opinions
	The theory is explained systematically to prove that his opinion on the topic of SSI problems is correct.
Verification	
Discussion	Students discuss in class or in groups opinions that have been supported by data, scientific explanations, and personal experiences so that appropriate conclusions are obtained based on the results of the discussion. Conclusions can be in the form of alternative solutions as a form of resolving the main SSI problem topic.
Communication	Students communicate the results of their discussions (conclusions/ alternative solutions) to the class in the form of oral presentations/ posters/ other scientific writing.
Reflection	Students evaluate the advantages and disadvantages of alternative conclusions /solutions as well as the implications of these solutions if applied to different.

The SSRI learning model has the advantage of presenting SSI as the core problem, which serves as a stimulus for students to practice arguing. The complex and controversial nature of socio-scientific issues can be utilized to improve students' argumentation skills (Martini et al., 2021; Zhu & He, 2022). When students are exposed to controversial SSI, they will engage in discussion, and debate that demand thinking skills, such as reasoning and evaluation of ethical issues, as well as the ability to make decisions regarding problem solutions (Evagorou et al., 2020). The integration of socio-scientific issues in learning creates a more meaningful learning experience compared to conventional methods, although it may present its challenges.

2.3. Data Collection Instrument

The instrument used to measure socio-scientific argumentation skills was an open-ended questions. In this research, the instrument was adapted from Toulmin's Argument Pattern [TAP] argumentation model (Toulmin, 2003). The argumentation skills instrument consisted of 20 open-ended questions containing discourse on SSI (see Supplementary file). The questions were designed in an open-ended form to encourage students to give concise and clear answers while still demonstrating structured reasoning. These questions lead students to construct well-structured arguments and articulate their thought processes clearly. This approach allows evaluation of the coherence and logical structure of students' arguments without burdening them with excessive writing demands. The aspects and indicators used can be seen in Table 3.

Table 3
Aspects and indicators of argumentation skills

Aspect	*Description*	*Indicators*	*Item number*
Claim	Express claims for socio-scientific problem solving.	Critical in responding to SSI about GMOs.	1, 2
		Generate ideas and answers about GMOs.	3, 4
Evidence	Show data or evidence that supports the claim.	Collect data/ facts that can prove claims made about GMO issues.	5, 6
		Classify the facts and data needed to solve the main problem in GMO issues.	7, 8
Warrant	Analyze the relationship between data and claims.	Analyze the relationship between data and claims in the context of GMO issues.	9, 10
Backing with contemplation	Explains the truth basis to support claims accompanied by empirical experience.	Explain the truth base to support claims about GMO issues.	11, 12
		Backing up claims with empirical experience on GMOs use.	13, 14
Rebuttal	Making statements that contradict data, warrant, or backing.	Provide counter evidence to arguments made about GMO issues.	15, 16
		Presenting alternative solutions to the GMO issues in overcoming food problems.	17, 18
Qualifier	Indicates the terms or conditions to which the claim applies	Provide certain conditions that make claims valid on the GMO issues.	19, 20

The argumentation skills instrument that has been designed is then validated through content validity and construct validity tests. The results of the content validity test show that each item has an Aiken [V] score above 0.76, which indicates that all items are valid. The construct validity test was conducted by testing the instrument on students who had completed the material on transgenic plants. Through Rasch model analysis, a Cronbach's alpha value of .72 was obtained, indicating that the instrument was reliable. The instrument was also analyzed using the variance explained by measure value, which resulted in a score of 37.2%, indicating a good value (Mokshein et al., 2019). In contrast, the unexplained variance value is in the range of 8.6%-12.3%, which indicates that the instrument is suitable for measuring argumentation skills (Fisher, 2007; Garg et al., 2021; Howells et al., 2020). Before the learning begins, students are given a pre-test question for argumentation skills that must be completed in 90 minutes. After the learning ends, they also do the argumentation skills posttest question at the same time.

Students' experiences include a variety of experiences that describe them during their learning with SSRI. Assessment of this experience is important to provide insight into the effects of SSRI learning and as a basis for further learning improvements. A total of 10 indicators that were decomposed into ten items of questionnaire statements about student experiences were carefully arranged according to the context, purpose and needs of the study. Seven biology education experts have validated this questionnaire to ensure its validity using Aiken's V statistics.

2.4. Data Analysis

The data analysis of the results of the socio-scientific argumentation skills tests compared the average scores of the pretest and posttest. Previously, the collected test score data were analyzed to determine data distribution using the Shapiro-Wilk test. The test results showed that the pretest and posttest scores were greater than $p > .05$, which means that the data were normally distributed. The pretest and posttest scores in CG and EG were also tested for homogeneity of variance using the Levene test. The test results showed a p-value > .05, indicating that the data was homogeneous. Therefore, to determine the difference in argumentation skills scores on EG and CG using parametric statistical tests. A paired sample t-test was used to determine the difference in pretest and posttest means of each aspect of argumentation skills in EG and CG. At the same time, the independent sample t-test was used to determine the difference in the mean posttest of each aspect of argumentation skills between EG and CG. Effect-Size [ES] was also measured using Cohen's d (Cohen, 1988) to determine the amount of influence on each aspect of argumentation skills in group (EG and CG). Effect-size values are classified as follows; $-.15 \leq d < .15$ negligible, $.15 \leq d < .40$ low, $.40 \leq d < .75$ medium, $.75 \leq d < 1.10$ large, $1.10 \leq d < 1.45$ very large, (1.45) d perfectly (huge) (Güler et al., 2022).

3. Results

The learning model was implemented in two classes (EG and CG) in biology education. Students are given pretest questions before learning, and at the end of learning they are given a posttest. Table 4 shows the descriptive statistics of the argumentation skills.

Table 4
Descriptive statistics of the pre and posttest argumentation skills

Aspect of argumentation skills	*Group*	*n*	*M*		*SD*		*Minimum*		*Maximum*	
			Pretest	*Posttest*	*Pretest*	*Posttest*	*Pretest*	*Posttest*	*Pretest*	*Posttest*
Claim	CG	46	62.91	74.05	10.41	9.31	37.50	56.25	81.25	93.75
	EG	44	62.22	85.23	8.33	9.44	50	62.50	81.25	100
Evidence	CG	46	60.19	67.39	11.74	9.49	43.75	50	81.25	81.25
	EG	44	61.22	77.70	12.10	9.08	43.75	56.25	81.25	100
Warrant	CG	46	61.96	71.47	13.93	10.43	37.50	50	87.50	87.50
	EG	44	61.36	77.84	13.16	10.39	37.50	50	87.50	100
Backing with contemplation	CG	46	60.46	69.43	9.86	9.34	50	50	81.25	81.75
	EG	44	60.09	76.14	8.33	8.87	50	56.25	81.25	100
Rebuttal	CG	46	61.82	68.34	12.02	11.81	50	50	81.25	87.50
	EG	44	61.51	75.43	19.51	9.28	50	50	81.25	100
Qualifier	CG	46	66.30	70.65	18.42	14.72	25	50	87.50	100
	EG	44	66.48	76.99	17.21	11.73	25	50	87.50	100
Overall Mean	CG	46	61.90	70.05	8.93	7.63	46.25	52.50	80	82.50
	EG	44	61.79	78.38	6.68	6.59	47.50	67.50	77.50	90

Table 4 presents the descriptive statistical results of each aspect of argumentation skills in EG and CG. In general, there was an increase in pretest to posttest scores on argumentation skills in

EG and CG. However, the average posttest for each aspect in EG was greater than the posttest for CG. The argumentation skills scores were then analyzed using a paired sample t-test to determine the difference in pretest-posttest scores for each aspect in EG and CG (see Table 5).

Table 5
Comparison of improvement in argumentation skills

Aspect	*Group*	*n*	*Paired sample t-test*		*Effect size (ES) (Cohen's d)*	
			t-value	*p-value*	*Point estimate*	*Interpretation*
Claim	CG	46	−6.261	.001	.923	large
	EG	44	−11.063	.001	1.668	perfectly
Evidence	CG	46	−5.528	.001	.815	large
	EG	44	-12.337	.001	1.210	very large
Warrant	CG	46	−4.611	.001	.680	medium
	EG	44	−5.928	.001	.894	large
Backing with contemplation	CG	46	−5.741	.001	.846	large
	EG	44	-12.309	.001	1.304	very large
Rebuttal	CG	46	−4.848	.001	.715	medium
	EG	44	−10.35	.001	1.186	very large
Qualifier	CG	46	−2.003	.051	.295	low
	EG	44	−5.598	.001	.650	medium

The results in Table 5 show that in each class (EG and CG), each aspect has a significant difference ($p < .05$), which means that the SSRI learning model effectively improves each aspect of argumentation skills in EG and the inquiry learning in CG (except the qualifier aspect, $p > .05$). At the same time, the ES value of each aspect in EG is greater than that of CG. This shows that the SSRI learning model provides a greater effect size than the inquiry learning in improving argumentation skills. To determine the significance of the difference in the average posttest score of argumentation skills between EG and CG, the data were analyzed with an independent sample *t*-test (see Table 6).

Table 6
Independent t-test of the posttest dependent variables (between-groups)

Aspect	*Group*	*n*	*Independent sample t-test*		*Effect size category (Cohen's d)*	
			t-value	*p-value*	*Point estimate*	*Interpretation*
Claim	CG	46	−5.65	< .001	1.192	very large
	EG	44				
Evidence	CG	46	−5.26	< .001	1.109	very large
	EG	44				
Warrant	CG	46	−2.90	.005	0.612	medium
	EG	44				
Backing with contemplation	CG	46	−3.49	< .001	0.736	medium
	EG	44				
Rebuttal	CG	46	−3.15	.002	0.665	medium
	EG	44				
Qualifier	CG	46	−2.26	.026	0.475	medium
	EG	44				
Overall Mean	CG	46	−5.53	< .001	1.166	very large

The results in Table 6 show that there are differences in posttest scores between EG and CG on all aspects of argumentation skills ($p < .05$). These results mean that the implementation of the SSRI learning model is better for improving argumentation skills than CG. ES values in 2 aspects obtained very large categories (claim, evidence) and four aspects obtained medium categories (warrant, backing with contemplation, rebuttal, qualifier). The highest ES value is in the claim aspect. The integration of SSI in inquiry learning makes students interested and motivated to identify the main issues/ problems in the context of the SSI so that they are trained to give their opinions about SSI correctly.

Table 7 shows the examples of arguments produced by students from the experimental group on the topic of GMOs, illustrating their argumentation skills.

Table 7
Example of student arguments in EG

Aspect and sample questions	*Student arguments*	*Rubric-based assessment*
Aspect: Claim		
Question: Herbicide-tolerant transgenic soybeans are considered more tolerant to glyphosate than regular soybeans (herbicide-intolerant). In your opinion, is it necessary to genetically engineer soybeans to be resistant to glyphosate? Explain!	I think genetic engineering of soybeans is necessary, because soybeans that are resistant to the herbicide glyphosate, farmers can more easily manage their fields by reducing weeds without reducing their yields.	Explain reason engineering genetics with argumentation discourse data based, covering danger glyphosate and its impact on quality of soybeans, in general logical, relevant, and systematic.
Aspect: Evidence		
Question: Research on the safety of tempeh from transgenic soybeans through subchronic testing in mice. The purpose of this study was to test the safety of tempeh from transgenic soybean through subchronic toxicity test using mice. For 90 days, three groups of mice (each consisting of seven mice) were fed rations containing tempeh flour from transgenic soybeans, tempeh flour from nontransgenic soybeans, and casein as the control. On the 90th day, all mice were sacrificed for blood and organ collection (see Table).	Based on the results of the study, there were no significant differences between rats that ate GMO, non-GMO, or control soybeans in terms of behavior, and bleeding/swelling indicators. The study also showed that transgenic soybeans did not trigger any health effects in rats, so transgenic soybeans are safe for human consumption.	Interpreting the result data study about security consumption soya bean transgenic compared to with non- transgenic soybeans by mice For support claim, with not enough complete (less from half parameters), logical, and systematic.
Aspect: warrant		
Question: In the genetic engineering process with gene transformation in transgenic soybeans, generally using Agrobacterium tumefaciens bacteria . What is the role of these bacteria in the genetic engineering process in transgenic soybeans?	The bacterium *Agrobacterium tumefaciens* is a vector for transferring genes. This bacterium is able to infect soybean plant tissue so that modified genes can enter soybean tissue and soybeans can express the modified gene trait. Agrobacterium is different from other bacteria because it has a TI plasmid that is able to transfer T-DNA into soybean plant cells.	Describes in detail and systematically the role of Agrobacterium tumefaciens in genetic engineering of transgenic soybeans by linking the TI plasmid to the bacteria and natural infection by the bacteria to the target plant (genomics).

Table 7 continued

Aspect and sample questions	*Student arguments*	*Rubric-based assessment*
Aspect: Backing with Contemplation Question: Do you have any empirical experience either personally or based on the experience of others in consuming transgenic plant products? Describe what the product is and what happened after you consumed it?	I have eaten imported fruits from abroad that are the product of GMO crops. The rot-resistant imported fruits were safe and delicious to eat. I did not experience any health problems after consuming them.	Provide evidence of personal/ other people's experiences that are counter-intuitive/refutational in the form of consequences, anticipations that can be made, negative or positive impacts/ influences in a clear, systematic and logical manner.
Aspect: Rebuttal Question: Glyphosate herbicide-tolerant soybeans are one alternative solution to overcome the world's food problems. What if in an environment free of soybean pests, is it still necessary to cultivate glyphosate herbicide-tolerant soybeans? Explain.	In my opinion, it is still necessary to cultivate, because it is possible that weed problems may arise in the future. However, if over time, the land is completely weed-free, it can be considered to plant non-GMO soybean crops without completely eliminating GMO soybean crops.	Explaining the choice (cultivation/not) clearly and systematically, by providing reasons for making glyphosate herbicide-tolerant soybeans by linking them to weed attacks or the quality of transgenic soybeans.
Aspect: Qualifier Question: After the successful engineering process of glyphosate herbicide-tolerant soybeans, soybeans can be cultivated to increase soybean production. In your opinion, how can we safely cultivate glyphosate herbicide-tolerant soybeans without harming the surrounding ecosystem/ environment?	How to cultivate transgenic (herbicide resistant) soybean plants: a) Use of glyphosate herbicide that is not excessive and measured according to needs; b) If weeds grow too much, then a combination of weed control with traditional techniques such as pulling weeds or pruning them is needed; c) It is necessary to alternate the cultivation of soybean plants between transgenic and non-transgenic, so as not to constantly use herbicides and also maintain biodiversity.	Explains how to cultivate transgenic soybeans by explaining the following points a) Ensuring successful expression of herbicide tolerance genes in transgenic soybeans, b) Controlled and efficient use of herbicides, c) Production/harvest that is not excessive by taking into account the needs and needs of ordinary soybean farmers.

Students' learning experience using the SSRI learning model was analyzed using descriptive statistics. Students' responses to the implementation of the SSRI learning model in EG are presented in Table 8.

Table 8 shows that all students (44) responded agree and strongly agree to implement the SSRI learning model in providing their learning experience. No students expressed disagreement or negative responses. This finding indicates that students in EG had a positive experience with implementing the SSRI learning model in their biology learning.

Table 8
Percentages of students' responses to the SSRI learning model

No	Learning experience	Disagree	Disagree less	Agree	Very agree
1	Extraction of initial knowledge	-	-	25	75
2	Problem identification of SSI	-	-	63.68	36.36
3	Determine the main topic of the SSI	-	-	56.82	43.18
4	Give an opinion on the main topic (pros and cons of SSI).	-	-	43.18	56.82
5	Provide explanations accompanied by scientific evidence.	-	-	65.91	34.09
6	Theoretically explain the topic of the SSI	-	-	31.82	68.18
7	Class and group discussions will conclude (alternative solutions).	-	-	45.45	54.55
8	Communicate the result of their discussion (conclusion/alternative solution) to the class.	-	-	59.09	40.91
9	Evaluate the advantages and disadvantages of alternative conclusions/solutions.	-	-	47.73	52.2
10	Explain the implications of the solution in different situations.	-	-	75	25

4. Discussion

The results showed a significant difference between the pretest and posttest scores of overall argumentation skills in EG and CG (Table 5). Based on the analysis of the aspects of argumentation skills, five aspects in EG experienced significant improvement, while in CG, only one aspect did not show significant differences (qualifier aspect). The interventions given to EG and CG resulted in differences in the final results, with the effect size value on EG being higher than that of CG. The mean posttest score of argumentation skills between EG and CG showed significant differences overall, including in each aspect of argumentation skills (Table 6). The effect size also showed that the intervention on EG had a positive impact on argumentation skills. These findings demonstrate the potential of the SSRI learning model in improving students' argumentation skills. The inquiry-based learning model with SSI integration provides a better impact on argumentation skills compared to the real-world application (level of inquiry) learning model without SSI integration.

4.1. The SSRI Learning Model in Experimental Group

The effectiveness of the learning model needs to be determined to find the extent of the instructional impact of the model on the objectives of the model development (Wicaksono, 2020). The effectiveness of the SSRI learning model has been shown to have positive results, namely improving students' argumentation skills in the SSI contexts compared to inquiry learning (Table 6). The stages in the SSRI learning model are specifically designed to train students' argumentation skills in the context of SSI. The integration of SSI in the inquiry approach plays a significant role in improving students' ability to argue. With SSI in inquiry learning, students are encouraged to put forward arguments, engage in debate, and think critically so that they can see and respond to an issue from an SSI perspective. This situation encourages the emergence of critical ideas from students as they respond and make decisions regarding the SSI at hand. Therefore, the SSRI learning model provides a stronger positive impact on the development of biology education students' argumentation skills than the traditional inquiry model without the integration of SSI. The debatable nature of SSI, relevant to contemporary issues and related to the context of everyday life, provides an interesting and challenging learning experience, helping students practice argumentation skills based on strong evidence. For example, a student in the experimental group presented an argument that demonstrated claims supported by relevant scientific evidence and reasoning that linked the process of genetic engineering to safety assurance (Table 7). This student's response reflected their ability to integrate scientific and social information in constructing an evidence-based argument. These findings are consistent with Dawson and Venville (2022) who highlight that incorporating socio-scientific issues into the learning process fosters students' ability to evaluate and develop well-reasoned arguments critically. This study's findings also align with a recent meta-analysis by Çalik and Wiyarsi (2024), highlighting the critical role of implementation duration and treatment type in SSI-based learning. In the meta-analysis, implementation duration was a significant moderator variable, whereas longer-term interventions substantially improved students' science literacy and argumentation skills. This supports the effectiveness of SSRI learning, designed to take place in four meetings in four weeks. By allowing sufficient time to explore the evidence, construct arguments, and consider different perspectives, students are better equipped to make strong claims, use relevant scientific data, and defend their arguments in academic discussions.

The SSRI learning model was developed to provide student-centered biology learning with the teacher acting as a facilitator (Dobber et al., 2017). The SSRI learning model is built on the inquiry model as the primary model, which has discovery characteristics (Wenning, 2011b). Theoretical and empirical support for the SSRI learning model comes from recent research, including 1) inquiry learning that is oriented towards argumentation activities has a positive impact on the quality of student’s written and oral arguments (Arslan et al., 2023; Demircioglu et al., 2023), 2) argumentation is practised in learning by using authentic problems as a stimulus so that students can identify problems, provide solutions and evidence in their arguments (Evagorou et al., 2020; Krell et al., 2024) organizing knowledge to provide an inquiry in social aspects empowers social interaction to help students gain ideas directly in everyday life. This method makes students more active in class, particularly in discussing and arguing, so they can maintain their study habits (Bossér & Lindahl, 2020). In addition, Çalik and Wiyarsi's (2024) meta-analysis also showed that treatment type in SSI-based interventions influences learning outcomes. SSRI-based learning integrates SSI in an inquiry approach, allowing students to understand scientific concepts, develop evidence-based arguments, and consider multiple perspectives. This is different from the inquiry learning model, which lacks explicit space for argumentation in the context of controversial socio-scientific issues. Therefore, this study strengthens the finding that the SSI-based inquiry approach is more effective than conventional inquiry in improving students' argumentation skills.

The SSRI learning model is applied to improve argumentation skills in the context of SSI. Learning activities are designed to develop various aspects of argumentation skills, namely: problem orientation, manipulation, generalization, verification, reflection. At the problem orientation stage, students are introduced to real-world issues that are complex, controversial, and contextually relevant. The SSI is presented through text and supported by learning media, such as a video on biotechnology about GMOs, which is currently a topic of debate in society. Students listen and identify the SSI, then determine the main topics related to GMOs. Through this activity, students are trained to think critically and develop argumentation skills in recognizing and analyzing contemporary social scientific issues that may be relevant to their own experiences. SSI encourages students to systematically identify the components of an issue, including scientific, social, economic and ethical aspects. SSI that are used as problems in learning can stimulate higher thinking, encouraging analysis, and argumentation (Dawson & Venville, 2022; Khishfe, 2022; Martini et al., 2021).

At the manipulation stage, students express their views on the key issues in GMOs and begin to take a position, either for or against them. Students look for strong evidence from various sources to support their position on the issue. This evidence strengthens students' arguments, either in favour or against the issues of GMOs. Through this activity, students are facilitated to explore the issue by collecting relevant evidence so that they can explore the issue in more depth. They are guided to critically evaluate information from multiple perspectives, ensuring their arguments are evidence-based. The third stage in learning is generalization; at this stage, students deepen their understanding of SSI-related theories or materials to strengthen their opinions. This theoretical material is explained in a structured way to show that their views on GMOs have a solid foundation. Solid evidence and theoretical support become the foundation for students in developing appropriate solution steps to deal with the GMO issues. Students are trained to have in-depth discussions and review various theories related to GMOs so that they can understand the topic more comprehensively. Through these discussions, they learn to analyze information critically, consider various perspectives, and develop structured arguments on issues related to GMOs. Discussion activities facilitate students to ask questions that drive their decisions and justify reasonable arguments (Faize et al., 2018; Nam & Chen, 2017). Learning in groups can increase mutual interaction between students. The process of discussion during argumentation and the presentation of counterarguments can encourage students to learn relevant information (Faize et al., 2018).

At the verification stage, students engage in group and class discussions that focus on the agreed solution to the GMO issues, that integrate scientific evidence and ethical considerations. These solutions include alternative proposals that are expected to be effective responses to the GMO issues. These discussions are reinforced by presentations and debates that encourage students to clarify arguments and deepen their understanding while helping them gain additional relevant information (Bossér & Lindahl, 2020; Faize et al., 2018). The utilization of SSI in learning has a positive impact on students' ability to debate and discuss with each other, thus improving their argumentation skills. Several studies explain that in an SSI learning environment, arguments can arise between those who agree and those who disagree with the SSI context. Students participate in debates between agreeing and disagreeing groups and show good performance in generating claims, warrants, and rebuttals (Lin, 2024). Students who debate in the SSI context will position themselves in one perspective/position of either agreeing or disagreeing (Christenson & Walan, 2023; Lin, 2023). Through SSI-based learning, students' skills in presenting arguments and dialoguing with peers develop significantly. At the reflection stage, students are invited to assess the strengths and weaknesses of the solutions that have been designed for the GMO issues, as well as consider the impact and effectiveness of these solutions when applied to different situations. This reflection activity not only helps students recognize the quality of their proposed solutions but also increases their awareness of their learning and problem-solving processes. Thus, students become more skilful in evaluating their approaches and are prepared to face similar challenges in the future (Li & Lajoie, 2022).

In this study, the SSI context has the theme of GMOs. Issues in GMOs, such as transgenic plant products, cloning, and clinical biotechnology, are interesting topics that encourage students to debate and argue. However, the SSI context in every country, and even in different regions within a country, may vary. In the future, SSI development in other themes needs to be implemented, for instance, in the theme of ecology. Ecological issues are popular issues that need to be raised as SSI in biology learning. Environmental problems are global problems and not just national issues (Genisa et al., 2020). In dealing with complex social issues such as GMOs, students are encouraged to analyze the problem from multiple perspectives: scientific, social, economic, and ethical aspects (Viehmann et al., 2024; Yerdelen et al., 2018). This multidimensional approach supports the development of a complex and holistic mindset in students, which is crucial in understanding and managing contemporary issues. Lecturers who implement SSI play a key role in helping students hone their argumentation skills. By engaging students in scientific practices such as observation, identification, analysis and inference of relevant issues, students are trained to construct arguments with strong evidence and solid logic (Alcaraz-Dominguez & Barajas, 2024; Fadzil, 2017). Recent studies have also shown that SSI-based learning has a positive impact on students' critical thinking and argumentation skills, especially on issues that require a multidisciplinary approach (Högström et al., 2024). Thus, through the SSRI learning model, students not only deepen their understanding of complex issues such as GMOs but also strengthen their ability to construct and defend rational and evidence-based arguments - an important skill in education and everyday life.

4.2. Inquiry Learning in Control Group

The results showed that the application of inquiry learning in the control group had a positive impact on various aspects of students' argumentation skills (Table 5). Specifically, significant improvements were seen in the aspects of claim, evidence, and backing with contemplation. Moderate improvements occurred in the aspects of warrant and rebuttal, while in the qualifier aspect, the effect was low. However, overall, the control group that applied inquiry learning showed less optimal results than the experimental group that used the SSRI model.

The improvement of argumentation skills in the control group can be attributed to the characteristics of inquiry learning that encourages discussion and debate among students, even though the topics discussed are not included in the SSI. Through this approach, students are trained to identify problems, discuss them in depth, develop claims, support arguments with evidence, and strengthen them by backing them with contemplation. This funding is in line with previous research, which states that inquiry-based learning is more effective than traditional methods in improving students' argumentation skills (Antonio & Prudente, 2021; Lunn Brownlee & Ryan, 2020; Songsil et al., 2019). This approach actively involves students in collecting data, analyzing information, and building evidence-based arguments (Putri et al., 2024).

However, the lack of SSI context in inquiry learning may be one of the factors why this model does not provide as good results as SSRI on some aspects of argumentation skills, such as rebuttal and qualifier. According to Zeidler et al. (2019), SSI contexts offer more complicated and controversial problems, which can increase students' cognitive engagement higher than non-SSI topics. Therefore, although inquiry learning provides significant benefits, the results of this study suggest that SSRI is more effective in training students to consider multiple perspectives and construct more in-depth arguments. This finding confirms the importance of the relevance of the learning context in developing students' argumentation skills. The inquiry learning improved basic argumentation skills, but the addition of SSI elements in SSRI provided a more complex and meaningful learning experience. This ultimately had a greater impact on all aspects of students' argumentation skills.

4.3. The Experiences of Students using the SSRI Learning Model

In its implementation, the SSRI learning model received positive responses from lecturers and students, indicating that this approach is considered an important innovation in the learning process. The responses from students in the experimental group showed that they gave a very positive response to the SSRI learning model (Table 8). Indicators that measure learning experience show that most students agree and strongly agree with this approach. This positive response reflects that the innovation of the SSRI learning model is indispensable in teaching biology, as it is able to create a fun and meaningful learning experience and effectively develop students' argumentation skills. Furthermore, the results of these student responses are in line with previous research, which shows that the application of innovative learning methods can have a positive impact on student engagement and motivation in the learning process (Jufrida et al., 2021; Muzammil, 2020). Thus, the SSRI learning model not only improves the understanding of biology concepts but also facilitates students in honing their critical and argumentative thinking skills, which are essential to prepare them to face challenges in the real world. Students' active and responsive involvement in this learning confirms that this approach is able to meet the needs of better and relevant education in the modern era.

Although the SSRI learning model has many advantages, it also faces some limitations. One aspect that needs to be further developed is the scope of learning topics, which is currently still focused on the GMO issues. This topic restriction may reduce the variety of learning contexts that appeal to students with different interests and backgrounds. Therefore, for future research, it is suggested that the SSI be extended to other important areas, such as environment, health and energy. This more diverse approach allows students to explore and analyze scientific issues that are more relevant to their daily lives, thus enriching their understanding and increasing interest in science. Another limitation is the generalizability of the results, given that the SSRI learning model is applied in a specific context. Variations in students' backgrounds, cultural factors, educational systems in schools or colleges, and differences in geographical locations affect the effectiveness of this model in various environments. In addition, this study only involved two classes in one college, so the results may be different if the SSRI model is applied on a wider scale or in other institutions. Including students from more diverse demographic backgrounds in the class may provide a more comprehensive perspective on the effectiveness of the SSRI model. External factors, such as family conditions and socioeconomic status, could also potentially influence students in developing argumentation skills. Despite these limitations, the results and findings of this study are expected to provide valuable insights into the potential of the SSRI model to improve students' argumentation skills in the context of SSI.

Finally, the application of the SSRI learning model proved to have a positive impact in improving students' argumentation skills. The results of a study comparing the experimental group using the SSRI model with the control group applying inquiry learning showed that integrating SSI in inquiry learning was more effective in developing biology education students' argumentation skills. This finding reinforces previous studies, although there are also studies showing that the inquiry approach can have a positive influence on students' argumentation skills. In addition, the integration of SSI in inquiry learning that is relevant to real-world situations provides a great motivational boost for students. The often controversial topics of SSI can arouse students' curiosity and interest in exploring critical issues from various perspectives. This approach leads students to actively seek additional information, evaluate the accuracy and relevance of data, and build solid arguments for solving SSI. Thus, the SSRI model not only increases learning interest but also prepares students to become individuals who are ready to face and contribute to complex issues in real life.

5. Conclusion

The SSRI learning model aims specifically to enhance students' socio-scientific argumentation skills in biology learning as an instructional impact. The SSRI learning model has a significant impact on argumentation skills compared to inquiry learning. The SSRI model was implemented over four weeks, allowing students to gradually develop more vigorous argumentation through a series of SSI-based inquiry stages. This duration provided sufficient time for students to explore the evidence, develop arguments, and evaluate different perspectives. Students' responses were also positive, as indicated by the answers of students who agreed and strongly agreed about their learning experience with the SSRI learning model.

SSI, as a problem stimulus, serves as a starting point for learning. SSI is used as a problem in the learning process to stimulate students to think on a higher level, encouraging activities such as arguing. The SSRI learning model that has been implemented has a positive impact on students' socio-scientific argumentation skills in biology learning. The implementation of the SSRI model creates an atmosphere of collaborative discussion, arguing, searching, and analyzing data and evidence to support opinions, as well as providing literature sources that can be accessed openly, thereby contributing to improving students' socio-scientific argumentation skills. Students have an essential role to play in the future development of good argumentation skills on SSI.

6. Recommendation

Even though the SSRI model contributes positively to argumentation skills in every aspect, its application by utilizing technology in learning needs to be further developed, especially e-learning, to support students in discussing at any time. The SSRI learning model can be implemented in biology learning by raising SSI in the fields of ecology, environmental pollution, global warming, food biotechnology, green technology, heredity, and energy in living systems. Further research can be carried out by including more schools or diverse geographical regions, which could provide broader information on how learning models interact within specific educational or community contexts.

7. Limitation

Although this study aims to test the effectiveness of the SSRI learning model as a means to improve students' argumentation skills, some limitations need to be recognized. First, the results of this study may have a limited degree of generalizability due to the specific context in which the SSRI learning model is applied. Variations in student backgrounds, including culture, school/ college education systems, and geographic location, can influence the effectiveness of learning models in different situations. Second, this research uses two class and is limited in sample size and diversity, so if the model were applied to a broader population, it might have a different impact. Small or homogenous sample sizes may hinder the ability to draw broad conclusions. Additionally, including diverse student demographics in the classroom can provide a more comprehensive understanding of the effectiveness of the SSRI learning model. Third, the duration of time needed to implement the SSRI learning model can be a limiting factor. Finally, external factors such as family conditions, socio-economic status, and community support can also influence argumentation skills. These factors need to be considered when interpreting the findings. Despite these limitations, it is hoped that the results and findings of this study will provide knowledge and insight into the potential of the SSRI learning model in promoting argumentation skills in the SSI context.

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