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Integrating GitMind into Socio-Scientific Inquiry-Based Learning: Impacts on Science Literacy and Argumentation Skills

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Article History:

Received: May 25, 2026
Revised: June 18, 2026
Accepted: June 26, 2026

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Keywords:

Socio-Scientific Issues, SSIBL, GitMind, science literacy, argumentation skills

Abstract:

Science literacy and argumentation skills are two essential competencies for addressing socio-scientific issues, yet both remain relatively low among high school students in Indonesia. No prior study has integrated digital mind-mapping tools within a Socio-Scientific Inquiry-Based Learning (SSIBL) framework to simultaneously develop these competencies, constituting the primary novelty of this work. This quasi-experimental study compared three instructional conditions: GitMind-assisted SSIBL, Guided Inquiry, and Direct Instruction. Participants were senior high school biology students studying the human reproductive and excretory systems, and ANCOVA was applied to control for pre-existing ability differences. The GitMind-assisted SSIBL class achieved the highest enhancement in science literacy (66.22%), outperforming Guided Inquiry (53.17%) and Direct Instruction (44.87%). Argumentation skills followed the same pattern, with SSIBL recording the greatest improvement (58.47%), followed by Guided Inquiry (46.09%) and Direct Instruction (34.35%). ANCOVA confirmed significant effects of instructional treatment on science literacy, $F(2, 89) = 63.615$, $p < .001$, partial $\eta^2 = .588$, and on argumentation skills, $F(2, 89) = 82.253$, $p < .001$, partial $\eta^2 = .649$. These findings provide theoretical support for the role of socioscientific context and digital knowledge externalisation in fostering higher-order competencies, and offer biology educators a structured, evidence-based instructional model applicable beyond conventional inquiry approaches.

INTRODUCTION

The advancement of science and technology in the twenty-first century has simultaneously generated new opportunities and produced a range of complex issues that place science at the centre of social, ethical, economic, and political debate. These issues are referred to as Socio-Scientific Issues (SSI), defined as contemporary problems rooted in scientific progress that admit no single correct answer, given that their resolution demands multidimensional consideration encompassing both scientific reasoning and societal values (Ariza et al. 2021; Zeidler et al. 2019). In biology education, SSI carry particular relevance because biological content intersects directly with real-world concerns such as reproductive health, the effects of pollution on organ function, the ethics of medical technology, and global climate change (Owens et al. 2021; Tran et al. 2024). Critical and responsible engagement with

such issues presupposes two mutually reinforcing core competencies, namely scientific literacy and scientific argumentation skills (Georgiou and Kyza 2023; Henderson and Mcneill 2017; Smit et al. 2025).

Scientific literacy refers to individuals' capacity to understand scientific concepts, evaluate evidence, and apply that knowledge to make responsible decisions in everyday life (OECD 2023; Tran et al. 2024). The PISA framework delineates three principal indicators of scientific literacy: explaining phenomena scientifically, evaluating and designing scientific enquiry, and interpreting data and scientific evidence (OECD 2023). Argumentation skills, in turn, encompass students' ability to construct and defend scientifically grounded positions through four core components: a claim that asserts a particular stance on an issue, data that serve as the empirical foundation for that claim, a warrant that articulates the logical reasoning connecting the data to the claim, and backing that provides additional support strengthening the warrant (Erduran 2018; Krell et al. 2024; Wess et al. 2023). Within the SSIBL context, these components are analysed through the Toulmin model of argumentation, which offers a structured lens for evaluating the quality and completeness of students' scientific reasoning (Erduran 2018; Mcneill and Katsh-singer 2016). These two competencies are fundamentally interdependent: scientific literacy furnishes the conceptual foundation students need to evaluate claims, while argumentation obliges them to articulate and defend those evaluations explicitly. Effective pedagogical interventions ought therefore to develop both competencies concurrently within a single integrated instructional design, as evidenced by prior research (Dawson and Carson 2018; Georgiou and Kyza 2023).

The actual state of Indonesian students' scientific literacy and argumentation skills remains far below expectations. The PISA 2022 results placed Indonesia's science literacy score at 383, considerably below the OECD average of 485, with only 34% of students attaining the minimum proficiency level (Antonio and Prudente 2024; OECD 2023). The most pronounced weaknesses are found precisely in the dimensions most central to SSI engagement, namely applying concepts in real-world contexts and critically evaluating scientific evidence (Nida et al. 2020; Owens et al. 2021). A comparable picture emerges with respect to argumentation: the majority of arguments produced by high school students remain at lower Toulmin levels, characterised by claims unsupported by adequate data, absence of warrants, and backing that is either weak or entirely missing (Krell et al. 2024). Preliminary needs analysis conducted by the researchers confirmed that only a small proportion of students could follow the steps of scientific enquiry, interpret scientific data, or make decisions grounded in scientific evidence. Collectively, these findings indicate that the problem extends beyond a knowledge deficit to a systemic inability to engage with science critically.

This deficit is closely associated with the persistence of teacher-centred instruction, limited effective learning time, and the inadequate integration of SSI into classroom practice (Ariza et al. 2021; Krell et al. 2024; Sadler et al. 2017). The root of the problem is fundamentally pedagogical: most science teaching approaches in common use continue to separate scientific knowledge from its social context, leaving students unpractised in connecting the two meaningfully (Henderson and Mcneill 2017; Owens et al. 2021). The Socio-Scientific Inquiry-Based Learning (SSIBL) model, developed by Levinson (2018), offers a promising pedagogical

response to this challenge. The model integrates scientific enquiry with SSI exploration through three sequential phases: Ask, Find Out, and Act. Unlike conventional inquiry models that concentrate primarily on scientific content, SSIBL explicitly positions social and ethical dimensions as integral components of the inquiry process itself, so that students not only seek scientific answers but also consider the social implications of their findings and defend their positions argumentatively (Amos and Levinson 2019; Georgiou and Kyza 2023). A growing body of research attests to the effectiveness of SSIBL in strengthening scientific literacy and promoting critical thinking, particularly in the context of socially relevant issues (Zeidler et al. 2019).

The implementation of SSIBL nevertheless presents genuine cognitive challenges that cannot be overlooked. Students are required to process simultaneously several types of heterogeneous information, ranging from scientific concepts and investigation data to social perspectives and ethical considerations, all of which must be integrated into a coherent argumentative structure (Ban et al. 2023). Such demands can exceed students' working memory capacity, especially in biology topics that are abstract and not directly observable. Visual thinking tools have attracted considerable attention as external scaffolding that assists learners in externalising, organising, and integrating information systematically. GitMind, a cloud-based digital mind-mapping platform, enables students to map relationships among ideas in real time, organise evidence visually, and trace the evolution of their thinking throughout the inquiry process (Fung and Liang 2023; Sari et al. 2025). The use of mind mapping is grounded theoretically in Mayer's (2024) multimedia learning theory, which holds that comprehension improves when verbal and visual representations are processed together within an integrated cognitive system, thereby reducing extraneous cognitive load and releasing capacity for deeper processing (Zhao et al. 2024).

A careful review of the existing literature reveals three significant and interrelated research gaps. Prior studies employing mind mapping in science education have generally treated it as a post-instruction consolidation tool, used after teaching to summarise content, rather than as active scaffolding embedded within each phase of inquiry; consequently, the potential of mind mapping as a real-time thinking instrument within an SSI inquiry cycle has yet to be explored (Badeo and Duque 2022; Zhao et al. 2024). Available SSIBL research has tended to examine a single competency outcome, most commonly scientific literacy or conceptual understanding, without integrating a visual thinking scaffold aligned to the four-component Toulmin argumentation structure of claim, data, warrant, and backing (Georgiou and Kyza 2023). Biology topics such as the human reproductive and excretory systems, which are conceptually dense, largely non-observable, and yet highly socioscientifically relevant, have received insufficient attention in SSI-based learning research, despite their direct connections to students' lived experiences and ethical decision-making. These three gaps point to the need for research that integrates SSIBL with phase-embedded digital mind-mapping scaffolding so as to develop scientific literacy and argumentation skills concurrently within a content-relevant context.

The present study responds to these gaps by proposing an integration that differs from prior work both conceptually and pedagogically. Conceptually, GitMind is repositioned as

active scaffolding embedded across all three SSIBL phases, rather than as a supplementary tool employed after instruction. During the Ask phase, students use GitMind to map socio-scientific issues and formulate inquiry questions visually; during the Find Out phase, the mind map serves as a real-time evidence organiser, helping students explicitly connect data to claims and articulate the warrants that justify that connection; and during the Act phase, the map structure provides a framework for assembling all four argumentation components claim, data, warrant, and backing into a coherent position prior to decision-making. This phase-embedded mechanism represents a new way of understanding how multimedia learning theory operates within an SSI inquiry cycle, something that has not previously been empirically tested. Pedagogically, the study targets two competencies concurrently within a single instructional design, while also investigating the differential contribution of each SSIBL phase to each competency outcome. This process-level analysis advances beyond the conventional pre-post comparison and affords deeper insight into the instructional mechanisms underpinning the effectiveness of the proposed integration. The selection of the human reproductive and excretory systems as the content domain is deliberate: both topics satisfy simultaneously the criteria of being conceptually dense and non-observable, thereby maximising the cognitive challenge that motivates visual scaffolding, and of carrying high socio-scientific relevance, making them an ideal testing ground for the proposed model. Grounded in this rationale, the present study aims to investigate the effect of GitMind-assisted SSIBL on students' scientific literacy and argumentation skills, and to examine how each learning phase contributes to both outcomes across the instructional process. The study is guided by three specific questions: first, whether GitMind-assisted SSIBL significantly affects students' scientific literacy relative to conventional instruction; second, whether GitMind-assisted SSIBL significantly affects students' argumentation skills; and third, how each SSIBL phase contributes to the development of both competencies throughout the learning process.

METHODS

This study employed a quasi-experimental approach using a pretest and posttest non-equivalent control group design involving three treatment groups to examine the effect of different instructional models on students' scientific literacy and argumentation skills. The research design is presented in Table 1.

Table 1. Research Design

Pretest	Treatment	Posttest
O1	X1	O2
O3	X2	O4
O5	X3	O6

Source (Leedy and Ormrod [2015](#))

Description:

X1 = SSIBL model assisted by gitmind class

X2 = Guided Inquiry model class

X3 = Direct Instruction model class

O1, O3, O5 = Pretest

O2, O4, O6 = Posttest

The study was conducted at SMAS Adabiah 2 Padang during the 2025–2026 academic year, with all eleventh-grade science students as the population. The sample consisted of three classes of 31 students each, totaling 93 students. Sample selection was carried out using purposive sampling based on two criteria: first, the class must offer biology as a specialization subject; and second, students must have access to personal or school-provided digital devices to support the use of GitMind during instruction. These criteria were established to ensure that both the content requirements and the technological demands of the SSIBL-GitMind treatment could be met consistently across groups. Once qualifying classes were identified, an equivalence test using one-way ANOVA was conducted based on students' prior academic report scores, with normality confirmed through the Shapiro-Wilk test and homogeneity verified through Levene's test. Results indicated no significant difference among the three classes ($F = 0.454$, $p = 0.636 > 0.05$), confirming their initial comparability, after which the three classes were randomly assigned to each treatment condition: SSIBL assisted by GitMind, guided inquiry, and direct instruction. The independent variable was the instructional model, while the dependent variables were scientific literacy and argumentation skills. Learning materials, instructional time, and assessment instruments were held constant across all groups throughout the study.

The intervention was delivered across eight instructional meetings (16×45 -minute periods) over eight weeks for each group, covering two biological topics: the excretory system and the reproductive system. In the SSIBL-GitMind group, GitMind mind-mapping software was integrated into the learning syntax at three specific phases. During the contextualization phase, students used GitMind to map the socioscientific issue presented, identifying key concepts and their relationships. During the investigation phase, GitMind was used to organize collected data and scientific evidence in a structured visual format. During the argumentation construction phase, students collaboratively built argument maps grounded in the Toulmin framework components directly within GitMind, enabling real-time peer review of argument structure. The use of GitMind at each phase was guided by purpose-designed student worksheets and facilitated by the classroom teacher throughout instruction.

The instruments used in this study included essay tests, lesson plans, student worksheets, and classroom observation sheets. Essay tests were administered as both pretest and posttest to measure scientific literacy and argumentation skills. The test instruments consisted of four sets of questions adapted from instruments previously developed and validated by other researchers. The science literacy test instrument for the excretory system topic was adapted from Intan (2025), with all items declared valid through Pearson product-moment correlation ($\text{sig.} < 0.05$) and a Cronbach's Alpha value of 0.73, while the science literacy instrument for the reproductive system topic was adapted from Anwar (2024), with an average validity value of 0.72 categorized as high and a Cronbach's Alpha value of 0.71. The argumentation skills test instrument for the excretory system topic was adapted from Akhwatunnisa (2025), with an average validity value of 0.66 categorized as high and a Cronbach's Alpha value of 0.72, and the argumentation instrument for the reproductive system topic was adapted from Rianti et al. (2024), with an average validity value of 0.67 categorized as high and a Cronbach's Alpha value of 0.90. All four instruments satisfied established criteria

for validity and reliability, confirming their suitability as data collection tools in this study. Argumentation skills were assessed using a rubric grounded in Toulmin's Argument Pattern (TAP), encompassing six components: claim, data, warrant, backing, qualifier, and rebuttal (Toulmin 2003; Erduran 2018), scored on a 1–4 scale per component. Scientific literacy items were aligned with the PISA framework, encompassing three competencies: explaining scientific phenomena, evaluating and designing scientific investigations, and interpreting data and evidence scientifically (OECD 2023). Lesson plans and student worksheets were designed to ensure fidelity of implementation across all treatment groups, while observation sheets monitored whether each instructional model was carried out as intended during each session.

The study was conducted in three stages. The preparation stage encompassed instrument adaptation, securing research permissions, and determining the sample groups. The implementation stage began with a pretest administered to all three groups, followed by eight weeks of instructional treatment, and concluded with a posttest. The final stage involved data processing and statistical analysis. Data analysis employed both descriptive and inferential statistics. Prior to hypothesis testing, normality and homogeneity of data were examined using the Shapiro-Wilk test and Levene's test respectively. Data meeting these assumptions were analyzed using one-way Analysis of Covariance (ANCOVA) to determine the effect of the instructional model on each dependent variable while statistically controlling for pretest scores, with a significance level set at $\alpha = 0.05$. Where significant differences were found, post-hoc comparisons were conducted using the Least Significant Difference (LSD) test to identify pairwise differences among the three treatment groups. This study was conducted in accordance with ethical standards applicable to educational research involving human participants. Formal institutional approval was obtained from the West Sumatra Provincial Education Office under reference number 000.9.2/235/PSMASLB/DISDIK-2026 prior to data collection. All participating students and their parents or guardians were informed of the research objectives and procedures, and written informed consent was obtained from all participants prior to the commencement of data collection. The confidentiality of participants' identities and individual data was maintained throughout the research process and across all forms of dissemination.

RESULTS AND DISCUSSION

The data obtained in this study were analyzed to determine differences in students' science literacy and argumentation skills across the three instructional conditions, namely GitMind-assisted SSIBL, Guided Inquiry, and Direct Instruction. Overall, the results consistently show that the GitMind-assisted SSIBL class achieved the highest gains in both outcomes. This pattern indicates that the combination of socio-scientific inquiry and digital mind mapping provides a more effective learning environment for developing science literacy and argumentation skills than inquiry alone or conventional teacher-centered instruction.

Science Literacy

The descriptive results for science literacy are presented in Table 2.

Table 2. Summary of Results of Descriptive Analysis of Science Literacy Data

Classes	Average		Difference	Enhancement (%)
	Pretest	Posttest		
Gitmind assisted-SSIBL	40,02	79,738	39,72	66,22
Guided Inquiry (GI)	39,516	71,673	32,16	53,17
Direct Instruction (DI)	39,113	66,431	27,32	44,87

All three groups demonstrated improvement from pretest to posttest, yet the magnitude of gain differed substantially across conditions. The GitMind-assisted SSIBL class achieved an N-gain of 0.662, exceeding those of Guided Inquiry (0.532) and Direct Instruction (0.449) by 0.130 and 0.213 points, respectively. Although all three values fall within the medium category, the absolute differences are not trivial: the SSIBL group's posttest mean (79.74) exceeded that of the Direct Instruction group (66.43) by more than 13 points, a gap that is both statistically significant and educationally meaningful. The indicator-level results provide a more granular account of where these gains originated, as presented in Figure 1.

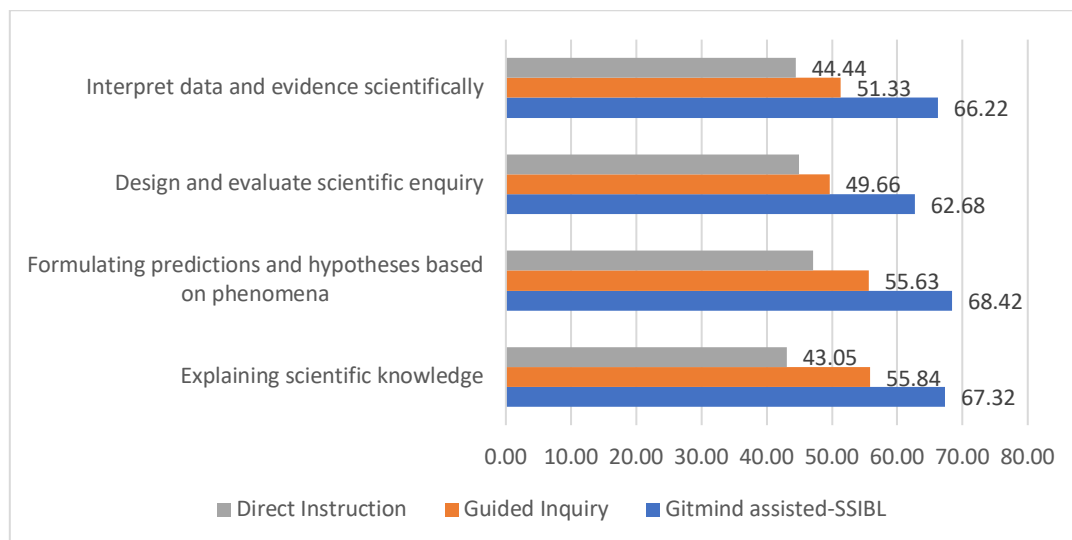


Figure 1. Percentage Increase by Indicator of Science Literacy

At the indicator level, explaining scientific knowledge produced the highest N-gain in the SSIBL class (N-gain = 0.6732; high category), compared with Guided Inquiry (0.5584; medium) and Direct Instruction (0.4305; medium). This finding is consistent with the argument that contextualising biological content, such as the physiological consequences of heavy metal exposure on renal function, within authentic socioscientific dilemmas demands a qualitatively different cognitive process from that required by conventional instruction. Specifically, students are required to transfer and apply declarative knowledge across multiple representational contexts, encompassing scientific, social, and ethical dimensions, an operation identified as a hallmark of advanced scientific literacy within the PISA 2022 science framework (OECD 2023). Importantly, however, the superior performance of the SSIBL class on this indicator cannot be attributed exclusively to the instructional design. The use of GitMind as a novel digital platform may have increased students' intrinsic motivation and attentional

engagement during the knowledge-construction phase, a confounding variable identified in the technology-enhanced learning literature as potentially inflating short-term learning gains in quasi-experimental studies (Galimova et al. 2025). The absence of a no-technology SSIBL control condition in the present design means this contribution cannot be isolated.

The indicator of formulating predictions and hypotheses also recorded a high N-gain in the SSIBL class (0.6842), compared with Guided Inquiry (0.5563; medium) and Direct Instruction (0.487; medium). The question-classification phase embedded within the SSIBL sequence, in which students sorted their initial questions into empirically resolvable and value-laden categories, appears to have operationalised an epistemic practice rarely scaffolded explicitly within conventional science curricula (Amos and Levinson 2019; Ariza et al. 2021). It should be noted, however, that the comparatively strong performance of the Direct Instruction class on this indicator (N-gain = 0.487) suggests that structured teacher-led presentation of inquiry procedures may offer a degree of procedural scaffolding that is not negligible, and that the advantage of SSIBL on hypothesis formation is therefore not unconditional.

The indicator of designing and evaluating scientific enquiry recorded medium-category N-gains across all three groups: 0.6268 (SSIBL), 0.4966 (GI), and 0.420 (DI). The convergence toward comparable N-gain values on this indicator, despite the pedagogical differences between conditions, merits analytical attention. One interpretation is that the procedural competencies associated with this indicator, namely selecting investigative strategies, evaluating source credibility, and documenting findings systematically, develop in response to any structured learning activity that includes an explicit inquiry or investigation component, and not solely through socioscientific inquiry (Lestari et al. 2024; Sasse 2025). The narrower spread of N-gain values across groups on this indicator, relative to the explaining scientific knowledge indicator, suggests that procedural inquiry skills may be more equally distributed across instructional formats than higher-order conceptual skills tied to authentic context engagement.

The indicator of interpreting data and evidence scientifically showed N-gains of 0.6622 (SSIBL; medium), 0.5133 (GI; medium), and 0.4444 (DI; medium). The stronger performance of the SSIBL class on this indicator aligns theoretically with the claim that structured evidence-evaluation activities, including cross-group comparison of GitMind maps and deliberate critique of competing knowledge representations, cultivate the kind of epistemic vigilance required for functional scientific literacy (Owens et al. 2021; Sari et al. 2024). Nevertheless, it remains plausible that differences in teacher facilitation quality across the three groups, an inherent limitation of quasi-experimental designs conducted in naturalistic classroom settings, contributed independently to the observed score differences on this indicator.

A summary of the ANCOVA results is presented in Table 3. The ANCOVA results confirmed statistically significant differences in science literacy across the three groups, $F(2, 89) = 63.615$, $p < .001$, partial $\eta^2 = .588$, indicating that instructional treatment accounted for 58.8% of the variance in posttest scores after controlling for pretest performance. The non-significant pretest covariate ($p = .732$) strengthens the inference that between-group posttest differences reflected genuine differential effects of instruction rather than pre-existing ability differences. These findings corroborate meta-analytic evidence that inquiry-based approaches yield large positive effects on higher-order scientific thinking (Antonio and Prudente 2024;

Arifin et al. 2025), while further suggesting that the integration of digital knowledge-externalisation tools into socioscientific inquiry produces additive gains on science literacy indicators that demand cross-contextual knowledge application.

Table 3. Summary of differences in students' Science Literacy

Source	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	2788,169 ^a	3	929,390	42,933	0,000	0,591
Intercept	6296,205	1	6296,205	290,851	0,000	0,766
Pretest	2,551	1	2,551	0,118	0,732	0,001
Kelas	2754,206	2	1377,103	63,615	0,000	0,588
Error	1926,633	89	21,648			
Total	495087,891	93				
Corrected Total	4714,802	92				

Argumentation Skills

The descriptive results for Argumentation Skills are presented in Table 4.

Table 4. Summary of Results of Descriptive Analysis of Argumentation Skills Data

Classes	Average		Difference	Enhancement (%)
	Pretest	Posttest		
Gitmind assisted-SSIBL	40,52	75,30	34,78	58,47
Guided Inquiry	38,10	66,63	28,53	46,09
Direct Instruction	37,50	58,97	21,47	34,35

The overall pattern for argumentation skills mirrored that observed for science literacy, with the SSIBL class attaining the largest N-gain (0.585), followed by Guided Inquiry (0.461) and Direct Instruction (0.344). The difference in N-gain between SSIBL and Direct Instruction (0.241) was considerably larger than that observed for science literacy (0.213), consistent with the ANCOVA result showing that instructional treatment exerted a stronger relative effect on argumentation (partial $\eta^2 = .649$) than on science literacy (partial $\eta^2 = .588$). This differential magnitude invites discussion of whether the mechanisms driving argumentation gains are more sensitive to the quality of peer-interactive, evidence-centred instruction than the mechanisms driving scientific literacy development, or whether this pattern reflects measurement artefact related to the specific difficulty distribution of the two assessment instruments. The indicator-level analysis covers four components of Toulmin's (2003) argumentation model, namely Claim, Data, Warrant, and Backing, and is presented in Figure 2.

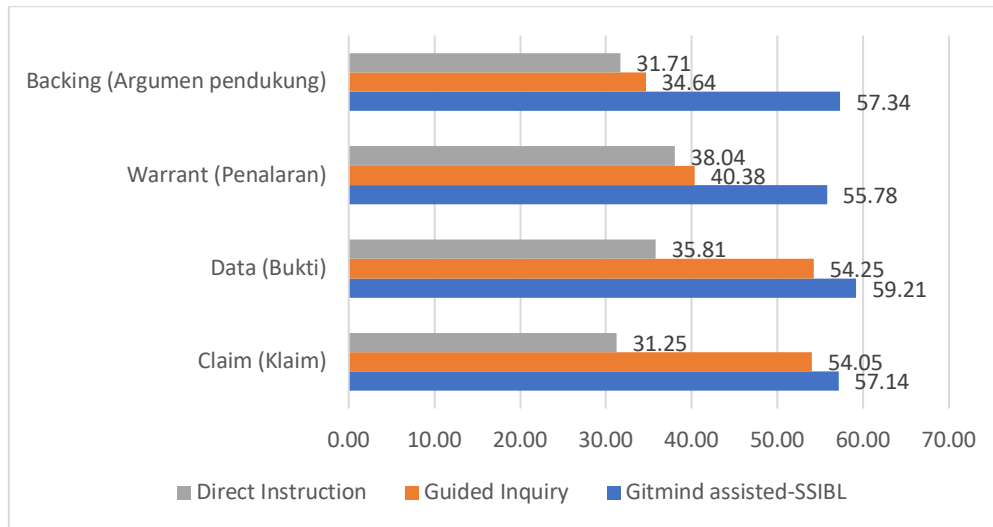


Figure 2. Percentage Increase by Indicator of Argumentation Skills

The Claim indicator recorded N-gains of 0.5714 (SSIBL; medium), 0.5405 (GI; medium), and 0.3125 (DI; medium). The relatively low N-gain in the Direct Instruction class on this indicator is theoretically informative. Within Toulmin (2003) the framework, a claim constitutes the foundational positional assertion from which all other argument components derive; without opportunities to actively construct and defend a position, students are unlikely to develop the epistemic agency required to formulate claims independently (Erduran and Jiménez-Aleixandre 2023). The teacher-centred format of Direct Instruction, while effective for transmitting propositional knowledge, affords students limited latitude to practise positional reasoning, an observation consistent with prior findings on SSI-based argumentation interventions (Aziz and Johari 2023). What is less straightforward is the moderate performance gap between SSIBL (0.5714) and Guided Inquiry (0.5405) on this indicator: both models provide structured opportunities for position-taking, suggesting that the SSI context, with its inherent value-laden ambiguity, may specifically motivate students to invest in claim construction in ways that topic-neutral guided inquiry does not (Sadler et al. 2017; Smit et al. 2025).

The Data indicator showed N-gains of 0.5921 (SSIBL; medium), 0.5425 (GI; medium), and 0.3581 (DI; medium). The Guided Inquiry class performed considerably closer to the SSIBL class on this indicator than on the Claim indicator, which is theoretically congruent: both inquiry-based models require students to search, evaluate, and apply empirical evidence as part of their investigative procedure, and the distinction between them on evidence use is therefore smaller than the distinction arising from their differential emphasis on authentic socioscientific context (Manz 2015; Mcneill and Katsh-singer 2016). The relatively low N-gain of the Direct Instruction class (0.3581) on this indicator suggests that passive exposure to teacher-presented evidence does not develop the ability to independently identify and deploy relevant evidence as effectively as student-driven evidence-gathering does.

A particularly informative pattern emerged for the Warrant indicator, which captures the logical connection between data and claim: the Direct Instruction class (N-gain = 0.3804)

performed below the Guided Inquiry class ($N\text{-gain} = 0.4038$), while both remained below the SSIBL class ($N\text{-gain} = 0.5578$). This pattern is theoretically congruent with the general hierarchy observed across indicators, yet the relatively narrow gap between Direct Instruction and Guided Inquiry on this component warrants attention. Structured, teacher-generated explanations provide students with explicit models of scientific reasoning by exposing them to systematic demonstrations of how evidence is connected to conclusions, a form of cognitive modelling that Guided Inquiry, in its emphasis on student-driven discovery, may not always provide with the same degree of explicitness (Sasse 2025). The Guided Inquiry class, by contrast, may have allocated a disproportionate share of cognitive resources to the data-collection phase, leaving insufficient instructional time for the explicit scaffolding of reasoning connections between evidence and claims, a deficit previously identified as a structural vulnerability of poorly orchestrated inquiry-based learning (Smit et al. 2025). This finding underscores that the Warrant component may require direct instructional scaffolding that neither unstructured nor semi-structured inquiry consistently provides.

The Backing indicator, which captures additional theoretical support that strengthens the warrant, produced $N\text{-gains}$ of 0.5734 (SSIBL; medium), 0.3464 (GI; medium), and 0.3171 (DI; medium). The most notable feature of the Backing data is that this indicator recorded the lowest absolute $N\text{-gain}$ values across all four argumentation components in the Direct Instruction and Guided Inquiry groups. This suppressed performance is not incidental: backing requires students to move beyond immediate empirical evidence toward broader theoretical grounding, a task that demands a higher degree of domain knowledge integration and epistemological sophistication than the other three Toulmin components (Erduran and Jiménez-Aleixandre 2023; Turós et al. 2025). The finding is consistent with research showing that warrant and backing consistently emerge as the most underdeveloped argumentation components across educational levels and subject domains (Mcneill and Katsh-singer 2016; Turós et al. 2025), and it suggests that a single instructional cycle, regardless of model, is insufficient to consolidate these higher-order argumentation components. The relatively stronger performance of the SSIBL class on Backing (0.5734 vs. 0.3171 in DI and 0.3464 in GI) may be attributable to the cross-group GitMind comparison phase, in which students were compelled to identify additional supporting positions when confronted with divergent peer representations (Krell et al. 2024); however, the contribution of teacher facilitation quality during these dialogic episodes cannot be excluded as an independent explanatory variable.

Table 5. Summary of differences in students' Argumentation Skills

Source	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	3853,080a	3	1284,360	58,230	0,000	0,662
Intercept	4798,518	1	4798,518	217,555	0,000	0,710
Pretest	19,075	1	19,075	0,865	0,355	0,010
Kelas	3628,440	2	1814,220	82,253	0,000	0,649
Error	1963,032	89	22,057			
Total	420400,391	93				
Corrected Total	5816,112	92				

A summary of the ANCOVA results is presented in Table 5. The ANCOVA results confirmed that differences in argumentation skills across the three groups were statistically significant, $F(2, 89) = 82.253, p < .001$, partial $\eta^2 = .649$. The instructional treatment accounted for 64.9% of the variance in posttest argumentation scores after controlling for initial ability. The non-significant pretest covariate ($p = .334$) confirms that between-group differences cannot be explained by pre-existing differences in argumentation proficiency.

Theoretical and Pedagogical Implications

The findings of this study carry theoretical implications that extend beyond confirmation of SSIBL's relative effectiveness. At the theoretical level, the data contribute to ongoing debates concerning the mechanisms through which science literacy and argumentation skills co-develop within inquiry-based instructional contexts. Prior research has established a positive correlation between these competencies, yet the causal pathways connecting them remain insufficiently specified (Krell et al. 2024; Smit et al. 2025). The present results provide evidence of a reciprocal developmental trajectory: gains in the science literacy indicator of interpreting data and evidence scientifically (N-gain = 0.654 in the SSIBL class) appear structurally connected to gains in the Data and Backing argumentation components (N-gains of 0.639 and 0.532, respectively), in a pattern suggesting that improved evidence-evaluation capacity strengthens argument construction, which in turn demands more sophisticated evidence engagement, producing further gains in scientific literacy (Amos and Levinson 2019; Georgiou and Kyza 2023; Zeidler et al. 2019). This reciprocal pattern is most clearly visible in the SSIBL class and was attenuated in the Direct Instruction class, where lower and more uniformly distributed N-gains across all indicators suggest that teacher-centred content transmission constrains the development of this interdependency.

A second theoretical contribution concerns the role of external knowledge visualisation in supporting argumentation quality. The Backing indicator, on which the SSIBL class achieved the strongest relative advantage, may be the component most directly mediated by the collaborative use of GitMind, given that visual comparison of divergent argument maps creates an immediate and salient prompt for students to locate and articulate additional theoretical support for their positions. This interpretation is consistent with the meta-analytic finding of Shi et al. (2023) that mind mapping-based instruction produces stronger cognitive learning gains than conventional instruction in science and technology subjects, and with theoretical accounts of the cognitive offloading function of external representations in complex reasoning tasks (Alsuraihi 2022; Mayer 2024). However, this interpretation carries an important caveat: the superior performance of the SSIBL class on Backing, and on most other indicators, cannot be attributed to GitMind in isolation. The richer peer dialogue, the authentic issue context, and the structured multi-phase inquiry sequence are each independently associated with argumentation gains in the SSI literature (Aziz and Johari 2023; Sadler et al. 2017), and the present design does not include a condition that isolates the effect of mind mapping from these co-occurring instructional features. Claims about the specific causal contribution of GitMind therefore remain speculative in the absence of a dismantling design.

The anomalous Warrant pattern, in which Direct Instruction marginally outperformed Guided Inquiry, carries a specific theoretical implication that has not received systematic attention in the comparative inquiry literature. If structured teacher explanation can partially compensate for the absence of collaborative peer investigation in developing the logical-connection dimension of argument, then the common framing of Direct Instruction as uniformly inferior to inquiry-based approaches for higher-order competency development requires qualification. The present finding suggests that the Warrant component, which involves making explicit the inferential logic connecting evidence to conclusions, may respond more strongly to direct modelling of reasoning than to open-ended evidence-gathering. Instructional designs that combine the context-richness and positional engagement of SSI with targeted, explicit scaffolding for inferential reasoning, rather than relying on peer dialogue alone to develop this competency, may therefore achieve stronger argumentation outcomes than either pure inquiry or pure direct instruction alone (Sasse 2025).

At the pedagogical level, the present study provides empirical evidence that integrating GitMind into SSIBL constitutes a practically viable strategy within the institutional and technological constraints of Indonesian secondary education. Indonesia's PISA 2022 science score of 383, which is 102 points below the OECD average, reflects persistent weaknesses in precisely the indicators that the present intervention targeted: contextual knowledge application and scientific data interpretation (Bilad et al. 2024; OECD 2023). The accessibility of GitMind as a free, browser-based platform reduces the infrastructural barriers that have historically limited the uptake of technology-enhanced science instruction in Indonesian schools (Nida et al. 2020). Nonetheless, the practical viability of the model is contingent on teacher facilitation quality, which is difficult to standardise across implementation contexts, and on student prior familiarity with collaborative digital tools, a factor that likely varies considerably across schools and regions.

Several limitations constrain the conclusions that can be drawn from this study and should inform the design of subsequent research. First, the intervention spanned eight instructional meetings, and the absence of a delayed posttest means that the durability of the observed gains cannot be assessed. Short-duration interventions are known to be susceptible to novelty effects in technology-enhanced learning contexts, where initial increases in student engagement may not persist as the novelty of a new platform diminishes (Galimova et al. 2025), and the present study cannot confirm whether the observed advantages of the SSIBL group would be maintained over a longer exposure period. Second, the single-school design in Padang limits the generalisability of the findings across institutional, socioeconomic, and regional contexts within Indonesia and beyond. Third, variation in teacher facilitation quality across the three groups, while monitored through structured observation schedules, may have introduced systematic uncontrolled influences that ANCOVA with a pretest covariate cannot fully mitigate. Fourth, the absence of a no-GitMind SSIBL condition means that the specific contribution of the digital mind-mapping tool cannot be separated from the contribution of the broader SSI instructional sequence. Future research should address these limitations by employing delayed posttests to evaluate retention, extending the intervention period to reduce susceptibility to novelty effects, incorporating active dismantling designs that isolate the

GitMind component, and conducting multi-site replications across diverse regional and institutional contexts.

CONCLUSION

This study demonstrates that the GitMind-assisted SSIBL model effectively enhances students' scientific literacy and argumentation skills in biology, outperforming both Guided Inquiry and Direct Instruction across all measured indicators. The instructional design, which embeds socioscientific dilemmas within a structured Ask–Find Out–Act sequence, fosters the kind of cross-contextual knowledge application and evidence-based reasoning that conventional approaches are less equipped to develop, with GitMind functioning not merely as a documentation tool but as a cognitive externalisation platform that made students' reasoning visible, comparable, and open to peer critique. These findings carry practical implications for biology educators seeking to integrate socioscientific issues more meaningfully into curriculum, particularly in topics where ethical and empirical dimensions naturally intersect. Nevertheless, several limitations must be acknowledged, including the quasi-experimental design, the absence of a no-technology SSIBL control condition, and the single school context, all of which constrain causal attribution and limit the generalisability of the findings. Future research should therefore examine this model's effectiveness across other biology topics and school contexts, explore the independent contribution of digital mind-mapping tools through controlled comparison, and investigate long-term retention of scientific literacy and argumentation gains beyond the immediate post-instructional period.

AUTHOR STATEMENTS

Funding

This research received no external funding and was conducted independently by the authors

Author Contributions

The first author conceptualized the study, designed the research methodology, developed the GitMind-assisted Socio-Scientific Inquiry-Based Learning (SSIBL) instructional framework, conducted the classroom intervention, collected and analyzed the data, interpreted the findings, and prepared the original manuscript draft. The second author contributed to the research design, supervised the implementation of the instructional intervention, validated the research instruments, assisted in data interpretation, and critically reviewed the manuscript for important intellectual content. The third author provided overall academic supervision, contributed to the theoretical framework and methodological refinement, critically revised the manuscript, and approved the final version for publication. All authors have read and approved the final manuscript and agree to be accountable for all aspects of the work.

Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article

Data Availability Statement

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Ethical Approval

This study was conducted in accordance with the ethical principles for educational research involving human participants. Ethical and institutional approval was obtained from the West Sumatra Provincial Education Office (Reference No. 000.9.2/235/PSMASLB/DISDIK-2026). Written informed consent was obtained from all

participating students and their parents or legal guardians prior to data collection. Participant confidentiality and anonymity were maintained throughout the study.

Acknowledgments

The authors would like to express their sincere gratitude to the West Sumatra Provincial Education Office for granting permission to conduct this research. The authors also thank the principal, biology teachers, and students of SMAS Adabiah 2 Padang for their cooperation, active participation, and valuable support throughout the implementation of this study. Appreciation is also extended to all experts who assisted in validating the research instruments and to everyone who contributed to the successful completion of this research. Their support has been invaluable in advancing research on socio-scientific inquiry-based learning, science literacy, and argumentation skills.

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