SPEKTRA: Jurnal Kajian Pendidikan Sains
Vol. 12, No. 2, 2026, pp. 521-534
ISSN: 2548-642X, DOI: 10.32699/drmex331

ENHANCING UNDERGRADUATE STUDENTS' SCIENTIFIC LITERACY THROUGH THE IMPLEMENTATION OF AN INQUIRY-BASED SOCIO-SCIENTIFIC ISSUES (SSI) MODEL

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Article Info

Article history:
Received 10/03/2026
Accepted 06/11/2026
Published 09/11/2026

Keywords:
Inquiry-based learning;
Scientific literacy;
Socio-scientific issues;
Test of scientific literacy skills (ToSLS)

ABSTRACT

This study aimed to analyze the effect of an inquiry-based Socio-Scientific Issues (SSI) learning model on the improvement of undergraduate students' scientific literacy compared to conventional instruction. The study employed a quantitative approach using a quasi-experimental pretest–posttest control group design. The experimental group received instruction through the inquiry-based SSI model, whereas the control group participated in the instructional approach commonly implemented in the classroom. Scientific literacy was measured using the Test of Scientific Literacy Skills (ToSLS) developed by Gormally et al. (2012), which was adapted to align with the instructional context. Data analysis was conducted using the Shapiro–Wilk normality test, Levene's test of homogeneity of variance, and a Welch independent-samples t-test to examine differences in gain scores. The data were normally distributed but not homogeneous; therefore, gain scores were analyzed using the Welch independent-samples t-test. The results revealed a highly significant difference in the improvement of scientific literacy between the experimental and control groups ($p < .001$). The experimental group demonstrated greater gains, particularly in organizing, analyzing, and interpreting quantitative data, as well as in evaluating evidence-based arguments. These findings indicate that the integration of socio-scientific issues and inquiry-based instruction is effective in fostering undergraduate students' scientific literacy. In conclusion, the inquiry-based SSI learning model was found to be more effective than conventional instruction in enhancing undergraduate students' scientific literacy in higher education.

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1. INTRODUCTION

Science education in higher education needs to prepare students to engage with increasingly complex scientific and societal challenges. Beyond understanding concepts and solving mathematical problems, university students need to be able to interpret scientific

information, assess the strength of evidence, and apply scientific knowledge when addressing problems in everyday life. In the PISA 2022 framework, scientific literacy means being able to work with science topics and use what you know about science to make smart choices and take part in society. The Organisation for Economic Co-operation and Development (OECD, 2023) emphasizes that scientific literacy encompasses more than the acquisition of disciplinary knowledge; It also means explaining things using science, checking and making plans for experiments, and looking at and understanding the information and proof gathered. These competencies are particularly important in higher education, where students are expected to develop into critical thinkers who can assess scientific claims and contribute meaningfully to discussions about science-related issues.

However, a growing body of research indicates that science instruction in higher education remains largely dominated by transmissive approaches that emphasize conceptual mastery and algorithmic–mathematical problem solving. In the context of biology education, (Andrews et al. (2019) found that active learning strategies had not fully replaced one-way instructional delivery, particularly in large-enrollment courses. Similarly, an evaluative study by (Klein et al. (2023) confirmed that traditional lecture-based methods continue to be the predominant instructional approach compared to active lecture models, despite evidence demonstrating the positive effects of active approaches on student engagement and retention. From a conceptual perspective, Loughlin (2025) explains that the persistence of lecture-dominated instruction in large classes is sustained by structural constraints, academic culture, and entrenched professional practices among faculty members. Taken together, these findings suggest that science teaching in higher education continues to prioritize conceptual coverage and algorithmic–mathematical problem solving through lecture-centered instruction, even though educational literature has long advocated for a shift toward more interactive and student-centered learning environments. This strong orientation toward conceptual and mathematical aspects consequently limits students' opportunities to meaningfully connect scientific knowledge with real-world issues emerging in society.

A growing body of research reports that undergraduate students' scientific literacy, including at the higher education level, remains within the low to moderate range and does not yet reflect optimal mastery of key competencies such as explaining phenomena scientifically, evaluating evidence, and interpreting data critically (Drummond & Fischhoff, 2017; Gormally et al., 2012; Murti et al., 2024; OECD, 2019; Sa'diyah & Putranta, 2026). Recent evidence from physics education contexts also indicates that undergraduate students may still experience difficulties in applying scientific concepts to real-world contexts, highlighting the need to strengthen scientific literacy through instructional approaches that engage students with evidence, scientific reasoning, and contextual problems (Sa'diyah & Putranta, 2026). Systematic reviews further indicate that improving scientific literacy remains an important concern in science education research, with increasing attention to instructional models that explicitly develop students' abilities to interpret scientific information, analyze evidence, and apply scientific knowledge in meaningful contexts(Murti et al., 2024). Results from the Programme for International Student Assessment (PISA), which is run by the OECD, show that most students reach only middle-level skills and are not yet able to use their science knowledge in a thoughtful way in real-life situations. Within higher education settings, (Gormally et al., 2012), using the TOSLS, found that many science undergraduates experience difficulties in interpreting data, understanding research design, and evaluating evidence-based claims. Similar results were

reported by (Drummond & Fischhoff (2017), who demonstrated that although students often possess foundational conceptual knowledge, they tend to exhibit weaknesses in evidence-based reasoning and the critical evaluation of scientific arguments.

In the Indonesian context, a range of empirical studies and both national and international reports indicate that students' and undergraduates' scientific literacy remains at low to moderate levels. Reports issued by OECD through the PISA have consistently placed Indonesia's scientific literacy performance below the OECD average. The majority of students perform at basic proficiency levels, primarily demonstrating the ability to recognize factual information and apply simple procedures, while showing limited capacity for complex scientific reasoning and in-depth evaluation of evidence (OECD, 2019, 2023). These findings are consistent with research conducted in Indonesian higher education institutions, which reports that undergraduates continue to experience difficulties in explaining phenomena scientifically, interpreting data, and evaluating evidence-based arguments. Studies involving both preservice science teachers and students enrolled in science programs reveal that scientific literacy competencies particularly in evaluating and designing scientific investigations, generally fall within the moderate range and tend to be relatively low on higher-order reasoning indicators.

This pattern suggests that science instruction in Indonesia continues to prioritize conceptual mastery and routine problem-solving over the development of reflective and contextualized scientific thinking. Furthermore, national assessments such as the Asesmen Nasional, administered by the Ministry of Education, Culture, Research, and Technology of the Republic of Indonesia, likewise indicate that literacy competencies including numeracy and scientific literacy remain among the primary challenges within the Indonesian education system. Taken together, this body of evidence underscores the need for systematic strengthening of scientific literacy in Indonesia through instructional innovations that place greater emphasis on inquiry, scientific argumentation, and the application of science to contextual and socio-scientific issues.

Based on these conditions, a gap exists between the competencies required in the twenty-first century and the prevailing practices of science instruction in higher education. On the one hand, scientific literacy is an essential competency for undergraduate students; on the other hand, instructional models remain largely oriented toward content transmission and mathematical problem-solving. This gap highlights the need for innovative instructional models that not only strengthen conceptual understanding but also systematically cultivate scientific literacy through authentic contexts and argumentative processes. Recent reviews indicate that SSI-integrated inquiry has been increasingly investigated in science education and has been associated with improvements in cognitive, affective, social, and scientific reasoning outcomes. However, previous studies have employed diverse inquiry structures and have not always made explicit how the instructional sequence connects the stages of engaging with an SSI, conducting inquiry, constructing evidence-based explanations, applying scientific knowledge, and reflecting on the implications of the findings. A recent systematic review of guided inquiry combined with SSI also indicates that existing studies have addressed outcomes such as science process skills, scientific argumentation, and critical thinking, suggesting that the field has moved beyond simply establishing the effectiveness of SSI-inquiry integration. Therefore, a remaining methodological issue is how the integration can be organized into a coherent and traceable learning sequence that explicitly supports the development of scientific literacy.

The novelty of this study does not lie simply in the integration of SSI and inquiry-based learning, as this integration has been examined in previous research. Rather, the contribution of this study lies in the development and empirical examination of a more explicitly structured instructional sequence that operationalizes the relationship between SSI contexts, scientific inquiry, and scientific literacy. The proposed model organizes learning into five sequential phases: Conceptualization, Observation, Justification, Actualization, and Reflection and Evaluation. These phases are designed to move students systematically from identifying and conceptualizing a socio-scientific problem, through evidence-based observation and scientific justification, to applying scientific knowledge and reflecting on the implications of their conclusions. Thus, SSI functions not merely as a contextual stimulus, but as the organizing context for a continuous inquiry process in which students construct, evaluate, and apply scientific knowledge. This structured linkage provides a methodological contribution by making the mechanism through which SSI-supported inquiry may foster scientific literacy more explicit and traceable. The study therefore extends previous SSI-inquiry research by examining not only whether an integrated approach is effective, but also how a structured sequence of learning phases can facilitate students' engagement with scientific information, evidence, and reasoning in physics learning.

The SSI instructional model offers substantial potential to bridge this gap. SSI-based learning introduces controversial and authentic science-related issues, such as climate change, genetic engineering, and energy resource choices, as relevant and meaningful contexts for instruction. Within this framework, students are encouraged to analyze scientific evidence, consider diverse scientific, social, and ethical perspectives, and construct evidence-based arguments before arriving at informed decisions regarding the issue under consideration (Högström et al., 2025; Sadler et al., 2016; Viehmann et al., 2024). In this way, SSI positions science learning not merely as the acquisition of content knowledge, but as engagement in complex and meaningful processes of scientific reasoning, argumentation, and decision-making. Recent systematic evidence further supports this potential, with a meta-analysis of SSI-based intervention studies reporting a large overall effect on students' scientific literacy (Çalik & Wiyarsi, 2025). Thus, SSI provides a pedagogical context in which scientific knowledge can be connected with evidence evaluation, higher-order thinking, and informed decision-making in authentic societal contexts. A key strength of the SSI approach lies in its capacity to enhance the relevance of instruction and to facilitate the integration of scientific content with broader social contexts. However, the implementation of SSI without a systematic inquiry structure may lead to discussions that are superficial and insufficiently grounded in empirical evidence.

Conversely, inquiry-based instruction has been shown to effectively foster science process skills, scientific reasoning, and data interpretation abilities (Furtak et al., 2012; Pedaste et al., 2015). Inquiry encourages students to formulate problems, design investigations, collect and analyze data, and draw evidence-based conclusions. Nevertheless, inquiry approaches that are not connected to social contexts may become confined to conceptual exploration without sufficiently addressing contextual decision-making. The integration of SSI and inquiry within a single instructional model is therefore considered capable of overcoming the limitations of each approach. SSI provides authentic contexts and opportunities for argumentation, while inquiry offers a systematic, data-driven methodological framework. Through this integration, students not only investigate scientific phenomena but also evaluate their social implications and make evidence-based decisions. This approach has the potential to strengthen the key indicators of

scientific literacy within the (Gormally et al. (2012) framework, particularly in identifying scientific problems, evaluating evidence, interpreting data, and drawing evidence-based conclusions.

The inquiry-based SSI learning model developed in this study was organized into five principal phases: (1) conceptualization, in which students are introduced to an authentic socio-scientific issue involving competing scientific, social, environmental, or practical considerations and are guided to activate prior knowledge, identify the central problem, and formulate initial questions; (2) observation, in which students investigate the issue through inquiry by collecting, examining, and interpreting relevant empirical or scientific information to identify evidence related to the problem; (3) justification, in which students analyze the evidence and construct scientific arguments to explain the issue, particularly by linking claims with supporting data and scientific reasoning; (4) actualization, in which students use the scientific knowledge and evidence obtained through inquiry to communicate reasoned decisions, evaluate possible alternatives, or propose solutions to the socio-scientific issue; and (5) reflection and evaluation, in which students critically evaluate the inquiry process, the adequacy of the evidence, the quality of their arguments, and the conceptual understanding developed throughout the learning process. Thus, SSI is embedded throughout the inquiry sequence rather than being used solely as an introductory context. The SSI serves as the authentic problem context that initiates inquiry, guides the search for and evaluation of evidence, provides the basis for scientific justification and decision-making, and becomes the object of reflection at the end of the learning process. This distinguishes the proposed model from conventional inquiry-based learning, which generally emphasizes investigation of scientific questions and construction of scientific explanations, by explicitly connecting the inquiry process with the analysis of real-world socio-scientific issues, evidence-based argumentation, decision-making, and consideration of the broader implications of scientific knowledge. Accordingly, the five phases establish a coherent instructional pathway linking SSI engagement, scientific inquiry, evidence-based argumentation, and informed decision-making within a single learning sequence.

Based on this rationale, this study aimed to examine the impact of an inquiry-based socio-scientific issues learning model on improving undergraduate students' scientific literacy in comparison with conventional instructional approaches. Scientific literacy in this study was measured using the TOSLS framework developed by (Gormally et al., 2012), which emphasizes argument evaluation, data interpretation, and evidence-based decision-making. This study is expected to provide a theoretical contribution to the development of contextual science instructional models in higher education, as well as empirical evidence regarding the effectiveness of integrating SSI and inquiry in enhancing undergraduate students' scientific literacy.

2. METHOD

A quasi-experimental design was implemented, with both experimental and control groups subjected to pre- and post-experimental assessments as part of the approach. Undergraduate students were enrolled in the Physics Education Study Program at Universitas Riau, Indonesia's Faculty of Teacher Training and Education. The selection of the participants occurred among two groups of students who were already studying physics courses that covered work, energy, momentum, and impulse. Out of the 57 undergraduates enrolled in the study, 30 were chosen for

the experimental group, and 27 were chosen for the control group. The selection of these two classes was made through random sampling. The experimental group was taught using the inquiry-based SSI learning model, while the control group was taught using the conventional instructional approach commonly used in the course. The Physics Education Study Program at Universitas Riau, Indonesia's Faculty of Teacher Training and Education was the focus of the study among fourth-semester undergraduates. Prior to the intervention, both groups took part in a test to determine their initial level of scientific argumentation. Following the instructional intervention, the same groups underwent a posttest to evaluate alterations in their scientific argumentation abilities.

Data on students' scientific literacy were collected through a pretest administered before the instructional intervention and a posttest administered after the intervention. Scientific literacy was measured using a modified version of the ToSLS developed by (Gormally et al. (2012), The adaptation was conducted to ensure that the instrument was appropriate for the characteristics of the participants, the physics learning context, and the objectives of the present study. The original ToSLS framework was kept as the main idea, especially its two big areas: (1) learning how to ask questions that help find scientific knowledge and (2) arranging, looking at, and making sense of numbers and scientific data. These domains include eight skills related to scientific literacy, such as assessing scientific arguments and their sources, understanding and working with scientific information, knowing how research is designed, presenting and reading numerical data, using math and numbers in science, and making conclusions based on evidence.

The adaptation process involved several stages. First, the original ToSLS items were reviewed to identify their relevance to the content and learning context of the present study. Second, the items were modified in terms of contextual situations, terminology, and examples to reflect the physics topics addressed in the intervention, particularly work, energy, momentum, and impulse, while maintaining the scientific literacy skills represented in the original instrument. Third, the adapted items were reviewed to ensure their alignment with the intended indicators and research objectives. The resulting instrument was then subjected to empirical validity and reliability testing before being used in the main study. Of the 18 adapted items initially developed, 16 items met the validity criteria, whereas two items were excluded based on the empirical validity analysis. The final instrument demonstrated good internal consistency, with a Cronbach's alpha coefficient of 0.854. These results provide empirical evidence supporting the validity and reliability of the modified instrument for assessing students' scientific literacy in the context of the present study.

The data was analyzed to check how well the model helped undergraduate students improve their scientific literacy, following three steps in order. Before the study began, both the experimental and control groups had their scores measured at the start and then again after the study was completed. Second, tests for normality and homogeneity were done to check how the scores in each group were spread out and how much they varied. The Welch independent-samples t-test was used to analyze the differences in gain scores between the two groups. The Shapiro–Wilk test of normality indicated that gain scores in both the experimental and control groups were normally distributed ($p > .05$). Given that the normality assumption was satisfied, parametric analysis was deemed appropriate. However, Levene's test for equality of variances revealed that the variances between the two groups were not homogeneous ($p < .05$), indicating differences in score variability between the experimental and control groups. Because the homogeneity assumption was violated, the analysis did not employ the standard independent-samples t-test;

instead, the Welch independent-samples t-test was used, as it is more robust to violations of the equal variance assumption.

3. RESULTS AND DISCUSSION

The Welch independent-samples t-test indicated a statistically significant difference between the groups, with a t-statistic of approximately 10.43 ($p < .001$). This value is well below the .05 threshold, indicating a highly significant difference in the improvement of scientific literacy between students in the experimental and control groups. Quantitatively, students who participated in the inquiry-based Socio-Scientific Issues (SSI) learning model demonstrated greater gains compared to those who received conventional instruction. These findings suggest that the implementation of the instructional model exerted a strong effect on the development of undergraduate students' scientific literacy. In other words, the observed improvement was not merely reflected in differences in mean scores but was also statistically significant. Therefore, the inquiry-based SSI learning model can be considered more effective than conventional instruction in enhancing undergraduate students' scientific literacy. The empirical evidence obtained in this study demonstrates that the improvement in undergraduate students' scientific literacy in the class implementing the inquiry-based Socio-Scientific Issues (SSI) model was not only statistically significant but also grounded in strong theoretical and empirical foundations. The obtained value ($t \approx 10.43$, $p < .001$) confirms that the difference in improvement between the experimental and control groups was not attributable to chance, but rather reflected a genuine effect of the instructional intervention. These results suggest that a learning design that deliberately integrates socio-scientific issues with inquiry processes can facilitate the development of scientific literacy competencies more effectively than conventional instruction.

Conceptually, these findings align with contemporary scientific literacy frameworks that emphasize the ability to explain scientific phenomena, evaluate scientific evidence, and make evidence- and data-informed decisions. Research conducted over the last decade has increasingly highlighted the potential of socio-scientific issues (SSI)-based instruction to foster scientific literacy, strengthen scientific reasoning, and promote higher-order thinking skills (Högström et al., 2025; Sadler et al., 2016; Viehmann et al., 2024). A recent meta-analysis further reported a large overall effect of SSI-based interventions on students' scientific literacy, providing quantitative evidence for the potential of SSI as a context for developing these competencies (Çalik & Wiyarsi, 2025) . In the context of contentious issues such as climate change and biotechnology, SSI-based learning also provides opportunities for students to engage with competing claims, evaluate evidence, and consider how scientific knowledge is constructed and justified. Such engagement can support epistemic cognition, particularly students' understanding of the nature, justification, and evaluation of scientific knowledge through evidence-based reasoning (Avraamidou, 2020; Viehmann et al., 2024)

The integration of an inquiry approach within this model further strengthens its impact. Recent research, including (Lazonder & Harmsen, 2016), indicates that explicitly structured inquiry-based learning has a significant effect on both conceptual understanding and data interpretation skills. When SSI is combined with inquiry, students are engaged not only in exploring scientific phenomena but also in evaluating the social and ethical implications of

scientific findings. This synergy helps explain the more pronounced gains in scientific literacy observed in the experimental group.

When analyzed in terms of the instructional syntax of the developed model, the mechanism underlying the improvement in scientific literacy can be understood more systematically. During the conceptualization phase, students identify and formulate problems grounded in authentic socio-scientific issues. Research within the SSI-based inquiry framework indicates that problem identification situated in real-world contexts enhances students' ability to evaluate evidence and engage in data-based decision-making (Zeidler et al., 2019). This phase contributes directly to the competency of understanding methods of scientific inquiry, a core indicator of scientific literacy. The observation phase facilitates students' engagement in collecting, organizing, and analyzing data. Recent studies indicate that active involvement in data analysis strengthens evidence interpretation skills and reduces misconceptions (OECD, 2019). At this stage, students directly develop their capacity to manage and interpret both quantitative and qualitative information. The actualization phase extends scientific literacy into the domains of reflection and decision-making. Contemporary research in 21st-century science education underscores the importance of this dimension, emphasizing that scientific literacy goes beyond conceptual mastery to include individuals' readiness to respond responsibly to science-based social issues(OECD, 2019; Zeidler et al., 2019). The actualization phase reinforces students' awareness of their roles as global citizens capable of integrating scientific evidence with social and ethical considerations.

Overall, the findings of this study align with research conducted over the past decade that supports the effectiveness of socio-scientific issues and inquiry-based approaches in improving scientific literacy. The significant gains observed in the experimental group can be interpreted as the result of an instructional design that systematically activates the conceptual, procedural, and epistemic dimensions of scientific literacy through a coherent sequence of learning phases. The inquiry-based SSI model developed in this study is therefore supported not only by statistical evidence but also by strong theoretical grounding and empirical validation within the contemporary landscape of science education research.

3.1. Scientific Literacy Achievement Across Categories

Undergraduate students' scientific literacy achievement, when analyzed by specific literacy categories, is illustrated in Figure 1.

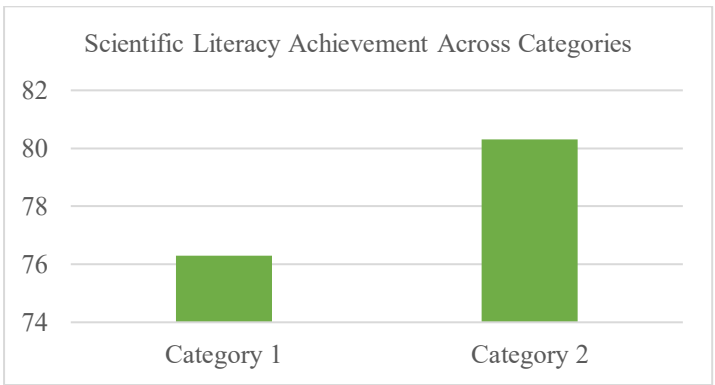


Figure 1. Scientific Literacy Achievement of Undergraduate Students Across Two Categories: (1) Understanding Scientific Inquiry Methods and (2) Organizing, Analyzing, and Interpreting Quantitative Data and Scientific Information

Based on Figure 1, which presents undergraduate students' scientific literacy achievement by category, the score for Category (2) organizing, analyzing, and interpreting quantitative data and scientific information was higher than that for Category (1), which pertains to understanding methods of scientific inquiry. The mean score for Category (1) was in the mid-70s, whereas Category (2) reached the low-80s range. This finding suggests that students demonstrated stronger performance in data analysis and quantitative interpretation than in developing a deeper understanding of how scientific investigations are conducted. In other words, while students appear to be relatively proficient in processing and interpreting data-driven information, their epistemological understanding specifically, how scientific knowledge is constructed and validated requires further development. The disparity between these categories indicates that the implemented instruction was effective in fostering data analysis skills; however, greater emphasis on research design, scientific procedures, and methodological reasoning is needed to promote more balanced development of scientific literacy.

An analysis based on the two primary categories of the ToSLS reveals a similar pattern. Students achieved higher scores in the second category, which emphasizes organizing, analyzing, and interpreting quantitative data, than in the first category related to understanding scientific methods of inquiry. This pattern is consistent with the findings of (Gormally et al. (2012), who reported that students tend to develop data interpretation skills more readily than competencies related to experimental design and methodological validity. Skills such as reading graphs, drawing conclusions from data, and evaluating relationships among variables are more frequently practiced in science instruction. In contrast, deeper understanding of variable control, potential bias, reliability, and validity requires more explicit instruction and structured epistemic reflection.

Students' comparatively strong performance in identifying scientifically valid arguments, assessing the credibility of information sources, developing and interpreting graphical representations, and drawing evidence-based conclusions suggests that they have attained a functional level of scientific literacy. That is, they are able to use scientific information to analyze problems and formulate evidence-based conclusions. However, comparatively lower scores in evaluating the misuse of scientific information and in solving advanced quantitative problems suggest that the dimensions of epistemic literacy and advanced quantitative reasoning require further strengthening. These findings correspond with earlier research showing that instructional strategies that actively engage students in analyzing data, evaluating evidence, and constructing and defending scientific claims through argumentation significantly improve ToSLS scores compared to transmissive forms of instruction (Furtak et al., 2012). National-level studies likewise demonstrate that problem-based and inquiry-oriented approaches yield greater gains in scientific literacy than traditional teaching methods, as students are directly involved in investigative processes and argumentative reflection.

The relatively strong achievement observed in the domains of data analysis and interpretation can also be explained by the characteristics of socio-scientific issue (SSI)– and inquiry-based instruction, which situate students in authentic contexts requiring evidence-based decision-making. (Lee et al., 2020) emphasize that the integration of SSI fosters students' epistemic engagement, particularly in evaluating evidence and formulating scientific conclusions. Similar findings have been reported in national studies, which consistently show that problem-based and inquiry-driven models effectively enhance scientific literacy by requiring students to conduct investigations, analyze data, and engage in critical reflection.

3.2. Scientific Literacy Achievement Based on Skill Components

Figure 2 illustrates undergraduate students' scientific literacy achievement across the specific skill components within the two scientific literacy categories.

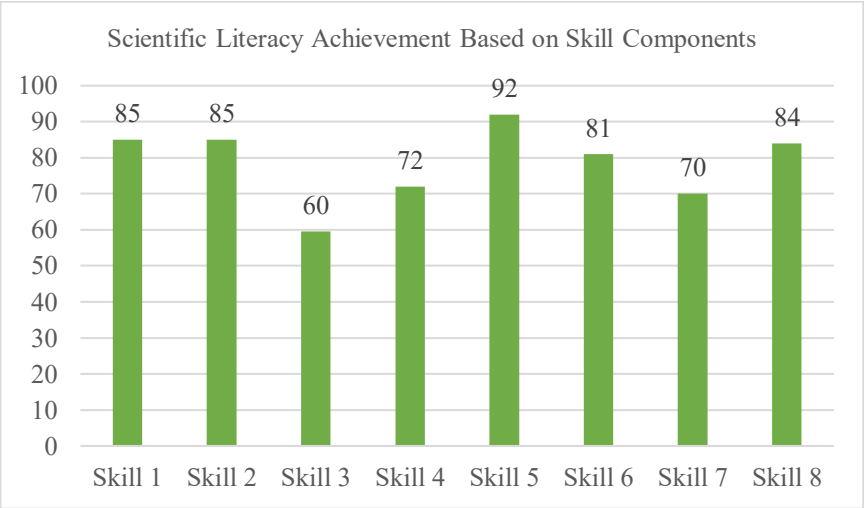


Figure 2. Undergraduate Students' Scientific Literacy Achievement Across Specific Skill Components

Figure 2 presents undergraduate students' scientific literacy achievement across eight specific skill components. The figure indicates variability in performance across these skills. Within the first category understanding methods of scientific inquiry Skills 1 and 2, which involve identifying valid scientific arguments and evaluating source credibility, obtained high scores in the upper-80 range. This achievement suggests that students have developed a relatively strong ability to distinguish valid arguments and assess the reliability of scientific information. However, Skill 3 evaluating the use and potential misuse of scientific information received the lowest score among all skills, falling within the 60s range. This result indicates that students' sensitivity to potential bias, data manipulation, or misinterpretation in scientific information requires further strengthening. Skill 4, which relates to understanding elements of research design and their impact on drawing conclusions, was categorized as moderate to high. This suggests that students possess a foundational methodological understanding, although it has not yet reached an optimal level.

In the second category quantitative data analysis Skill 5 (constructing graphical representations of data) and Skill 8 (justifying inferences and conclusions based on data) demonstrated high achievement. These results indicate that students are relatively proficient in visually presenting data and drawing appropriate conclusions from quantitative evidence. Skill 6, involving reading and interpreting graphs, also showed strong performance, although slightly lower than Skill 5. Meanwhile, Skill 7, which concerns problem-solving using quantitative reasoning, including probability and statistics, was categorized as moderate. This finding suggests that more complex numerical reasoning remains challenging for some students. Overall, this performance pattern indicates that students' scientific literacy is relatively strong in data analysis and interpretation, as well as in identifying valid scientific arguments. However, the ability to detect the misuse of scientific information and to solve advanced quantitative problems requires further reinforcement. Thus, the development of scientific literacy has not been evenly distributed

across all skill components, and future instructional interventions should focus on strengthening areas that remain at a moderate level to promote more balanced competency development.

A more detailed analysis of the eight scientific literacy skills reveals that students performed highly in identifying valid scientific arguments and evaluating the credibility of sources. This reflects the development of critical scientific literacy, characterized by critical engagement with scientific information. Inquiry-based SSI instruction provides opportunities for dialogue, evidence-based debate, and claim evaluation, thereby supporting the growth of this competency. However, the relatively lower performance in evaluating the misuse of scientific information highlights a crucial challenge. In the context of widespread misinformation, this skill is essential because it requires more complex metacognitive and epistemic reasoning. With respect to understanding research design and its influence on conclusions, students' performance was categorized as adequate, although not yet optimal. (Osborne et al., 2016) argues that the ability to evaluate the quality of an investigation including the reliability and validity of data, requires explicit instruction on the structure of scientific argumentation and methodological justification. Without systematic conceptual guidance, students tend to interpret data descriptively, without critically examining the appropriateness of the research design or potential sources of bias. In the quantitative domain, students demonstrated strong performance in constructing and interpreting graphs and in justifying data-based inferences. However, performance in problem-solving tasks involving advanced probability and statistics remained within the moderate range, a finding consistent with OECD reports highlighting persistent challenges in advanced numerical aspects of scientific literacy.

The measurable improvement in scientific literacy, as assessed through the ToSLS, is closely associated with the instructional syntax of the inquiry-based SSI model implemented in this study. Each phase of the model contributed directly to the two primary domains of scientific literacy assessed by ToSLS: understanding methods of scientific inquiry and quantitative data analysis. The conceptualization phase encouraged students to identify authentic scientific issues, activate prior knowledge, and formulate investigable questions. This stage supported students' ability to recognize valid scientific arguments and distinguish evidence-based claims from opinion. The observation phase constituted the core of the inquiry process, during which students collected and analyzed empirical data. Improvements in data interpretation indicate that this phase effectively strengthened skills in reading graphs, identifying patterns, and evaluating relationships among variables. The justification phase linked data to claims through scientific reasoning. At this stage, students were required to defend their conclusions based on evidence, thereby reinforcing the argumentative dimension of scientific literacy. The actualization phase extended scientific literacy into the social domain, as students were tasked with formulating positions or proposing solutions to the issues under discussion. This aligns with the view that authentic scientific literacy must include an applicative and social dimension namely, the capacity to use scientific knowledge and practices in decision-making processes that have societal implications (Zeidler et al., 2019). The reflection and evaluation phase strengthened the metacognitive dimension by encouraging students to reassess their investigative processes and the quality of their conclusions.

Overall, the findings indicate that inquiry-based SSI instruction significantly enhanced students' scientific literacy, both statistically ($p < .001$) and substantively across multiple competency dimensions. Students demonstrated improvements not only in analytical abilities but also in evaluative and argumentative capacities. Nevertheless, this development was not entirely

uniform; deeper epistemological understanding and the ability to detect the misuse of scientific information remain areas requiring further reinforcement. The findings demonstrate that the inquiry-based Socio-Scientific Issues (SSI) learning model can enhance students' scientific literacy in higher education. Beyond the observed quantitative gains, the findings indicate improvements across the applicative, analytical, and reflective dimensions of scientific literacy, although the extent of improvement varied across specific skills. These findings suggest that the integration of SSI with a structured inquiry process can provide students with opportunities to engage with scientific information, analyze evidence, apply scientific knowledge, and reflect on scientific issues in meaningful contexts.

Nevertheless, several limitations should be acknowledged. First, the study was conducted with a relatively limited sample from a single higher education institution and within a specific physics learning context; therefore, the findings should not be generalized to other student populations, institutions, or disciplinary contexts without further evidence. Second, the intervention focused on selected physics topics, particularly work, energy, momentum, and impulse, which may limit the extent to which the findings represent scientific literacy development across broader physics content. Third, the study examined changes in scientific literacy following a specific instructional intervention and therefore provides limited evidence regarding the sustainability of these gains over a longer period. Future research should therefore examine the implementation of the inquiry-based SSI model across larger and more diverse samples, including students from different institutions and educational contexts. Longitudinal studies are also needed to investigate whether improvements in scientific literacy are sustained beyond the instructional intervention. Further studies could extend the model to other physics topics and examine how the model influences specific scientific literacy skills that showed relatively greater need for instructional refinement. Comparative studies involving different inquiry designs or instructional approaches may also provide deeper insight into the mechanisms through which SSI-based inquiry contributes to scientific literacy development. Overall, the study contributes empirical evidence concerning the use of a structured SSI-inquiry approach in higher education physics and provides a basis for further refinement and broader implementation of the model.

4. CONCLUSION

Drawing on the findings of the data analysis and the subsequent discussion, the study concludes that the inquiry-based Socio-Scientific Issues (SSI) learning model significantly improves undergraduate students' scientific literacy compared with conventional instructional approaches. The improvement is evident not only descriptively in terms of score gains, but also statistically, as indicated by the highly significant difference between the experimental and control groups. When examined through the framework of the ToSLS, the model effectively strengthens the two primary domains of scientific literacy: (1) understanding the methods of scientific inquiry and (2) organizing, analyzing, and interpreting quantitative data. Although achievement in data analysis and interpretation was relatively higher than in methodological understanding, overall the inquiry-based SSI model fosters multidimensional development of scientific literacy, encompassing analytical, evaluative, and argumentative competencies. The findings suggest that integrating socio-scientific issues with an inquiry approach represents a strategic alternative for science instruction in higher education. Instructors should design learning experiences that extend

beyond mathematical problem-solving and conceptual mastery, providing opportunities for students to engage in investigation, evidence-based argumentation, and critical reflection on the validity and limitations of scientific evidence. Furthermore, the results indicate the need for continued emphasis on students' ability to evaluate the misuse of scientific information and to understand research design, as these aspects showed comparatively lower achievement. Future research may focus on developing more explicit epistemic scaffolding strategies or on testing the model across different scientific disciplines to examine the consistency of its effectiveness. In conclusion, the inquiry-based SSI model holds strong potential as a meaningful contribution to science education by promoting relevant, contextualized, and comprehensive development of undergraduate students' scientific literacy.

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