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Effect of IoT-Assisted Sociobiological Case-Based Learning on Students' Scientific Explanation Ability in Water Pollution

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ABSTRACT

This study investigated the effect of an Internet of Things (IoT)-assisted Sociobiological Case-Based Learning (SCBL) model on students' scientific explanation ability in the water pollution topic. Scientific explanation is essential for constructing evidence-based claims and logical reasoning, yet its development using authentic IoT-generated environmental data remains understudied. This study employed a quasi-experimental method using a non-equivalent control group design. The participants consisted of 40 students in Class X1 as the experimental group, who learned through the IoT-assisted SCBL model, and 32 students in Class X2 as the control group, who received Discovery Learning instruction. Scientific explanation ability was assessed using six essay questions based on the Claim–Evidence–Reasoning (CER) framework. The data were analyzed using the Shapiro–Wilk normality test, Levene's test for homogeneity of variance, and the Mann–Whitney U test. The experimental group achieved a higher normalized gain (N-gain = 0.68) than the control group (N-gain = 0.55), with both categorized as moderate. The Mann–Whitney U test revealed a significant difference between groups (Asymp. Sig. (2-tailed) = 0.035, $p < 0.05$) with a moderate effect size ($r = 0.25$). The greatest improvement in the experimental group was observed in the Reasoning indicator (N-gain = 0.73, high category) and the integrated CER indicator (N-gain = 0.71, high category). These findings indicate that integrating the SCBL model with real-time IoT sensor data provides an effective and evidence-based approach to enhancing students' scientific explanation ability in biology learning.

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INTRODUCTION

Scientific explanation ability is a fundamental competency in twenty-first-century science education because it reflects the quality of students' scientific reasoning and conceptual understanding (McNeill & Krajcik, 2012; Wangmo et al., 2025). Rather than merely communicating scientific information, scientific explanation involves a structured reasoning process in which students formulate claims, support them with empirical evidence, and justify those claims using appropriate scientific reasoning (National Research Council, 2012; Duschl et al., 2021). Consequently, scientific explanation is widely recognized as a key indicator of meaningful science learning because it demonstrates students' ability to integrate scientific knowledge and evidence rather than simply recall factual information. Accordingly, the Next Generation Science Standards (NGSS) identify scientific explanation as one of the core science and engineering practices that students should master (National Research Council, 2012; Osborne, 2014)(National Research Council, 2012; Osborne, 2014).

In Indonesia, the Merdeka Curriculum emphasizes the development of critical reasoning and scientific literacy by encouraging students to connect scientific concepts with authentic phenomena encountered in everyday life (Hunaepi & Suharta, 2024; Kementerian Pendidikan Riset, dan Teknologi, 2022). This emphasis is consistent with Osborne & Patterson (2011), who argue that scientific explanation is a central component of scientific literacy because it requires learners to construct evidence-based arguments and critically evaluate scientific evidence. Therefore, strengthening students' scientific explanation ability has become an essential objective of contemporary science education.

Despite its importance, students' scientific explanation ability remains limited. Preliminary observations through interviews with biology teachers revealed that students tend to describe biological phenomena narratively without formulating scientific claims, selecting relevant empirical evidence, or providing logical reasoning based on scientific concepts. These weaknesses correspond to the three components of the Claim, Evidence, and Reasoning (CER) framework proposed by McNeill & Krajcik (2012). Previous studies similarly report that students' limited scientific explanation ability is associated with instructional practices that emphasize memorization, provide insufficient opportunities for data-driven inquiry, and rarely engage students in authentic contexts requiring independent scientific explanation (Nofiana, 2017; Wanloh & Nuangchalerm, 2022). A similar pattern of underdeveloped critical thinking has also been reported among junior high school students on other science topics, reinforcing the need for instructional innovation (Ngongo et al., 2026).

Water pollution represents a particularly relevant topic for developing scientific explanation ability because it is a complex environmental phenomenon involving interactions among physical, chemical, and biological factors while simultaneously affecting ecosystem sustainability and human health. Understanding water pollution requires students to analyze cause-and-effect relationships, integrate empirical evidence with scientific concepts, and construct coherent scientific explanations. These characteristics directly support the development of the Claim, Evidence, and Reasoning components within the CER framework. Furthermore, as an authentic environmental issue that can be directly observed, water pollution provides meaningful opportunities for students to connect scientific concepts with real-world data (Nubita & Istianah, 2024). Phenomenon-based ecological learning has also been shown to improve students' ability to relate environmental evidence to scientific concepts and strengthen evidence-based explanations (Khikmah et al., 2024). Similarly, interactive learning media developed around ecology and biodiversity topics have been shown to strengthen students' science process skills when engaging with environmental phenomena (Lazulfa et al., 2025).

One instructional approach with strong potential to address these challenges is Sociobiological Case-Based Learning (SCBL), an extension of Case-Based Learning (CBL) that integrates authentic sociobiological issues into biology instruction (Zeidler, 2014). Through the analysis of real-world cases reflecting interactions between biological phenomena and social contexts, SCBL encourages students to think critically, interpret scientific evidence, and make evidence-based decisions. According to Herreid (2007), case-based learning promotes higher-order thinking by engaging students in authentic contexts that require scientific analysis and decision-making. Within the SCBL framework, authentic sociobiological cases stimulate students to analyze evidence, discuss alternative explanations, and construct scientifically justified claims (Sadler, 2011). Previous studies have demonstrated that SCBL significantly improves biological literacy, critical thinking, and scientific explanation ability by

encouraging learners to connect biological concepts with authentic social and environmental contexts (Suwono et al., 2017; Wanloh & Nuangchalerm, 2022). These findings are consistent with those of Mushlich & Sunarmi (2024), who reported that SCBL effectively enhances students' problem-solving skills. In addition, McNeill & Krajcik (2008) emphasized that learning activities structured around the CER framework and authentic cases substantially improve the quality of students' scientific explanations.

The effectiveness of SCBL can be further enhanced through the integration of Internet of Things (IoT) technology. IoT enables students to obtain real-time measurements of water quality parameters, including pH, temperature, turbidity, and Total Dissolved Solids (TDS), using digitally connected sensors (Halawa et al., 2025; Ramlowat & Pattanayak, 2019). The availability of authentic empirical data is essential for developing scientific explanation because the Evidence component of the CER framework requires valid and relevant observations derived from systematic investigations (McNeill & Krajcik, 2012). Furthermore, previous studies have shown that IoT-based learning improves students' scientific reasoning, inquiry skills, analytical thinking, and scientific literacy by providing immediate access to authentic environmental data (Bu'u, 2023; Dusturia et al., 2024; Ramlowat & Pattanayak, 2019; Wisdayana et al., 2025). This is consistent with broader evidence that integrating digital technology into classroom learning models can enhance student engagement and learning outcomes (Lisdayanti et al., 2025).

Although previous studies have demonstrated the effectiveness of SCBL in promoting scientific reasoning and the usefulness of IoT in supporting inquiry-based science learning, these approaches have generally been investigated separately. Existing research has primarily examined SCBL as an independent instructional model or employed IoT solely as a technological tool for environmental data collection, without integrating both approaches within a unified instructional framework. This limitation is important because effective scientific explanation requires both meaningful problem contexts and valid empirical evidence. While SCBL provides authentic socio-biological contexts that stimulate scientific reasoning, IoT supplies real-time environmental data that strengthen students' evidence-based explanations. To date, limited empirical evidence has examined the combined effects of integrating SCBL and IoT on students' scientific explanation ability, particularly in the context of water pollution learning. Therefore, this study addresses this research gap by integrating SCBL with IoT-assisted environmental monitoring and examining their combined effects on students' Claim, Evidence, and Reasoning competencies.

Previous studies have also reported that socio-scientific issue-based learning contributes positively to students' critical thinking, environmental awareness, and conceptual understanding (Afifa et al., 2021; Isnaini & Rahayu, 2023; Maolida et al., 2024). Similarly, environmental context-based instructional media, such as Education for Sustainable Development (ESD)-based e-modules integrated with a flipped classroom approach, have been shown to improve students' self-awareness competencies, achieving a moderate N-Gain score of 0.62 (Purnawati et al., 2023). Nevertheless, empirical evidence remains limited regarding how students' scientific explanation ability develops when authentic environmental cases are combined with real-time IoT sensor data within an integrated SCBL learning environment.

Based on these considerations, this study aimed to investigate the effect of the IoT-assisted Sociobiological Case-Based Learning (SCBL) model on students' scientific explanation ability in learning about water pollution. Scientific explanation ability was assessed using the Claim, Evidence, and Reasoning (CER) framework developed by McNeill & Krajcik (2012). This study is expected to provide empirical evidence regarding the effectiveness of integrating SCBL and IoT as a contextual biology learning innovation that utilizes authentic environmental data to comprehensively enhance students' scientific explanation ability.

METHOD

Research Design

This study employed a quantitative approach using a quasi-experimental method with a non-equivalent control group design. This design was selected because the experimental and control groups

were assigned purposively rather than randomly while maintaining relatively comparable initial characteristics (Sugiyono, 2023). The experimental group was taught using the Internet of Things (IoT)-assisted Sociobiological Case-Based Learning (SCBL) model, whereas the control group received Discovery Learning instruction. Both groups completed a pretest before the intervention and a posttest after the intervention to assess students' scientific explanation ability on the water pollution topic. The research design is presented in Table 1.

Table 1. Non-Equivalent Control Group Pretest–Posttest Design

Group	Pretest	Intervention	Posttest
Experimental group	O_1	X_1	O_2
Control group	O_3	X_2	O_4

Note: O_1 and O_3 represent pretest measurements; O_2 and O_4 represent posttest measurements. X_1 represents IoT-assisted Sociobiological Case-Based Learning (SCBL), and X_2 represents Discovery Learning.

Population and Sample

The study was conducted at a public senior high school in Sukabumi City during the 2025/2026 academic year. To ensure anonymity during the peer-review process, the name of the school is withheld. The study population comprised Grade X students. The sample consisted of 40 students from Class X1 as the experimental group and 32 students from Class X2 as the control group, selected through purposive sampling based on the predetermined selection criteria. Ethical approval for this study was obtained from the relevant institutional research ethics committee, and written informed consent was obtained from all participating students and/or their parents or legal guardians prior to data collection.

Research Instruments

Scientific explanation ability was assessed using a test consisting of six essay items developed based on the Claim–Evidence–Reasoning (CER) framework proposed by McNeill & Krajcik (2012). The same instrument was administered as both the pretest and posttest. Prior to its implementation, the instrument was piloted with 36 Grade XI students and analyzed using Anates 4 software. Item validity was evaluated using the Pearson product–moment correlation, with all six items meeting the validity criterion ($r = 0.846–0.961$; Item 1 = 0.930, Item 2 = 0.896, Item 3 = 0.873, Item 4 = 0.961, Item 5 = 0.905, and Item 6 = 0.846). Instrument reliability was assessed using the Kuder–Richardson Formula 20 (KR-20), yielding a reliability coefficient of 0.94, indicating excellent internal consistency. Furthermore, all items demonstrated good-to-excellent discrimination indices (42.5%–62.5%) and moderate difficulty indices (66.25%–68.75%), confirming the overall quality of the instrument.

In addition, the experimental group completed a learning implementation observation sheet to evaluate the fidelity of the IoT-assisted Sociobiological Case-Based Learning (SCBL) model and a 16-item student response questionnaire to examine students' perceptions of the learning experience. The response categories for both instruments (e.g., Excellent and Good) were interpreted according to the classification proposed by Widoyoko (2009), as presented in the Results section.

Data Analysis

Data were analyzed using SPSS version 25.0. First, pretest and posttest scores were calculated for both the experimental and control groups, and students' learning improvement was determined using the normalized gain (N-gain) formula (Hake, 1999). Prior to hypothesis testing, the data were subjected to the Shapiro Wilk normality test and Levene's test for homogeneity of variance. Depending on the results of these prerequisite tests, group differences were analyzed using either the Independent Samples t-test or the Mann Whitney U test.

Analysis of covariance (ANCOVA), which is commonly used to adjust for baseline differences between groups, was not applied because the N-gain data did not satisfy the normality assumption required for ANCOVA (see Table 3). Instead, the N-gain approach was employed to account for differences in students' initial abilities, following the recommendation of Sugiyono (2023) for data that violate parametric assumptions. In addition, gender was examined descriptively to explore whether the learning model showed a broadly similar pattern of effectiveness across male and female students. This

analysis was exploratory in nature and was not included as part of the primary hypothesis testing; therefore, no inferential statistical comparison was conducted between gender subgroups.

RESULTS AND DISCUSSION

Effect of the IoT-Assisted SCBL Model on Students' Scientific Explanation Ability in the Water Pollution Topic

Essay items based on the CER framework were employed to measure the extent of students' scientific explanation ability in the water pollution topic. The pretest, posttest, and N-gain results of the experimental and control groups are presented in Table 2.

Table 2. Pretest, Posttest, and N-gain Results of the Experimental and Control Groups

Class	Mean Score		N-gain	Category
	Pretest	Posttest		
Experimental	58	86	0,68	Moderate
Control	49	77	0,55	Moderate

The N-gain results of the experimental and control groups yielded the same criterion, namely moderate. The N-gain score of the experimental group was 0.68, classified as moderate, and the N-gain score of the control group was 0.55, also classified as moderate. This is consistent with (Hake, 1998), who categorizes N-gain scores into three criteria: high if $g > 0.7$; moderate if $0.3 \leq g \leq 0.7$; and low if $g < 0.3$. Although both groups were in the same category, the experimental group demonstrated a higher posttest score than the control group. The moderate improvement obtained by the control group is consistent with prior evidence that Discovery Learning can meaningfully enhance students' cognitive mastery and problem-solving skills, even without additional technological support (Assidik et al., 2026).

Subsequently, the pretest and posttest scores of both groups were subjected to prerequisite analysis tests, comprising normality and homogeneity tests. The normality test was conducted to determine whether the data were normally distributed. Upon ascertaining the data distribution, a homogeneity test was performed to determine whether the data had homogeneous variance. Given the significant difference in pretest scores, N-gain was calculated to control for initial ability differences, and the N-gain values between groups were subsequently compared using the Independent Sample t-test or the Mann-Whitney U test, depending on the normality test results. A summary of this analysis is presented in Table 3.

Tabel 3. Statistic Test

Test	Class	Description	Scor (Sig.)	Description
Normality Test (Shapiro-Wilk)	Experimental	Pre-Test	0,307	Normally Distributed
	Control	Pre-Test	0,093	Normally Distributed
	Experimental	N-Gain	0,000	Not Normally Distributed
	Control	N-Gain	0,005	Not Normally Distributed
Homogenity Test (Pre-Test)	Experimental & Control	Based on Mean	0,160	Homogeneous Variance
Homogenity Test (N-Gain)	Experimental & Control	Based on Mean	0,351	Homogeneous Variance

Test	Class	Description	Scor (Sig.)	Description
Pre-test Difference Test (*Independent t-test*)	Experimental & Control	Sig. (2-tailed)	0,002	Significant Difference
Hypothesis Test (*Mann-Whitney U*)	Experimental (Mean Rank: 41,45) Control (Mean Rank: 30,69)	Asymp. Sig. (2-tailed)	0,035	Significant Difference
Effect Size	Experimental & Control	Effect Size	0,25	Sedang

The significant difference in pretest scores ($p = 0.002$) indicates that the experimental and control groups were not fully equivalent in their initial scientific explanation ability. This limitation is inherent in the non-equivalent control group design with purposive sampling employed in the present study. To minimize the influence of these baseline differences, the analysis focused on normalized gain (N-gain) rather than raw posttest scores, thereby accounting, to some extent, for variations in students' initial abilities. Nevertheless, this approach cannot entirely eliminate the possibility that pre-existing differences between the two groups contributed to the observed outcomes. To complement the significance test, the effect size for the Mann-Whitney U test was calculated, yielding an r value of 0.25, which indicates a moderate effect. Collectively, these findings suggest that the IoT-assisted Sociobiological Case-Based Learning (SCBL) model produced a statistically significant, albeit moderate, improvement in students' scientific explanation ability. Because SCBL and IoT were implemented as a single integrated instructional intervention, the individual contributions of each component could not be examined independently. Accordingly, the observed effect should be interpreted as the combined effect of the integrated IoT-assisted SCBL approach rather than the effect of either component in isolation.

These findings are consistent with previous studies demonstrating that authentic case-based learning environments requiring evidence analysis, collaborative discussion, and claim construction effectively promote students' scientific reasoning (Sadler, 2011; Zeidler, 2014). Within the SCBL model, this process is facilitated through five instructional stages: (1) orienting students to a sociobiological problem, (2) organizing students to develop problem-solving strategies, (3) conducting collaborative investigation or inquiry, (4) developing and presenting inquiry findings, and (5) analyzing and evaluating the problem-solving process (Suwono et al., 2017; Wanloh & Nuangchalerm, 2022). Unlike previous studies that implemented SCBL without real-time environmental data, the present study integrated IoT technology to provide direct measurements of water quality parameters, including pH, temperature, turbidity, and Total Dissolved Solids (TDS). These authentic quantitative data enabled students to support their explanations with concrete empirical evidence, thereby strengthening the Evidence component of the Claim–Evidence–Reasoning (CER) framework (Bu'u, 2023; Halawa et al., 2025; McNeill & Krajcik, 2012).

Students' Scientific Explanation Ability on Each CER Indicator

Students' scientific explanation ability on each CER indicator was analyzed following the calculation of pretest and posttest scores for the experimental and control groups. N-gain was subsequently calculated to assess the improvement of ability on each indicator. The N-gain results are presented in Figure 1.

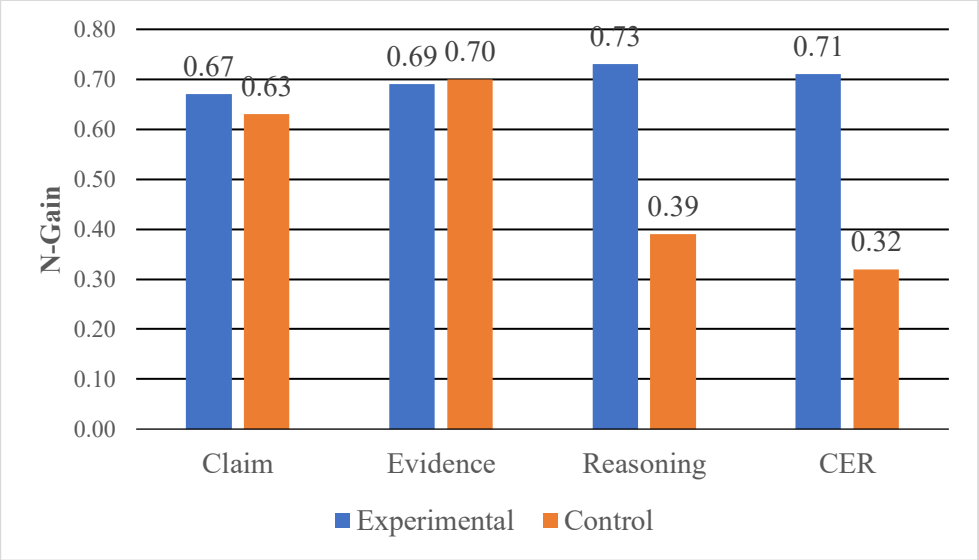


Fig.1. N-gain per scientific explanation indicator

The N-gain values were calculated based on pretest and posttest scores for each CER indicator and interpreted using Hake's (1998) criteria: high ($g > 0.70$), moderate ($0.30 \leq g \leq 0.70$), and low ($g < 0.30$). Based on the N-gain values in Figure 1, students' scientific explanation ability in the experimental group demonstrated superiority over the control group on the majority of indicators. On the Reasoning indicator, the experimental group achieved an N-gain of 0.73, classified as high, while the control group reached only 0.39, classified as moderate. On the integrated CER indicator, the experimental group attained an N-gain of 0.71 (high category), while the control group achieved only 0.32 (moderate category). On the Claim and Evidence indicators, both groups were in the same moderate category, although the experimental group still demonstrated superiority on the Claim indicator (0.67 versus 0.63). A unique finding emerged on the Evidence indicator, where the control group (0.70) slightly exceeded the experimental group (0.69); however, this negligible difference is not substantively meaningful.

The greatest improvements were observed in the Reasoning and integrated Claim–Evidence–Reasoning (CER) indicators. This finding is likely attributable to the use of real-time quantitative data generated by IoT sensors during the investigation process, which provided students with authentic empirical evidence to support the construction of logical scientific reasoning. Specifically, students were able to interpret numerical measurements of turbidity, temperature, pH, and Total Dissolved Solids (TDS) to explain the causal relationships between changes in water quality and their impacts on aquatic organisms (McNeill & Krajcik, 2008; Wisdayana et al., 2025). In contrast to previous studies implementing SCBL without real-time environmental data, where improvements across the Claim, Evidence, and Reasoning components tended to be relatively balanced (Suwono et al., 2017), the present findings suggest that integrating IoT technology particularly strengthens the Reasoning component by providing direct, evidence-based support for scientific justification. This interpretation should, however, be made with caution because the study design evaluated SCBL and IoT as a single integrated intervention, making it impossible to isolate the independent contribution of the IoT component. Nevertheless, the findings align with the theoretical perspective that Reasoning is the most cognitively demanding component of the CER framework, requiring students to integrate conceptual understanding, interpret empirical data, and construct scientifically valid arguments to justify the relationship between evidence and claims.

Students' Scientific Explanation Ability Based on Gender

A descriptive, exploratory gender-based analysis of scientific explanation ability was additionally conducted to examine whether the pattern of improvement was broadly consistent for male (M) and female (F) students within each group. This analysis was not part of the study's primary hypothesis, and no inferential statistical test was conducted between gender subgroups; the N-gain

values below should therefore be read as descriptive trends rather than statistically confirmed differences. N-gain data by gender across all CER indicators are presented in Table 4 and Figure 2.

Table 4. Students' Scientific Explanation Ability Based on Gender per Indicator

Indicator	Gender	Experimental		Control	
		N-Gain	Category	N-Gain	Category
Claim	Male	0,61	Moderate	0,55	Moderate
	Female	0,59	Moderate	0,63	Moderate
Evidence	Male	0,70	Moderate	0,71	High
	Female	0,63	Moderate	0,70	Moderate
Reasoning	Male	0,68	Moderate	0,30	Moderate
	Female	0,79	High	0,45	Moderate
Claim-Evidence-Reasoning	Male	0,71	High	0,27	Moderate
	Female	0,71	High	0,39	Moderate

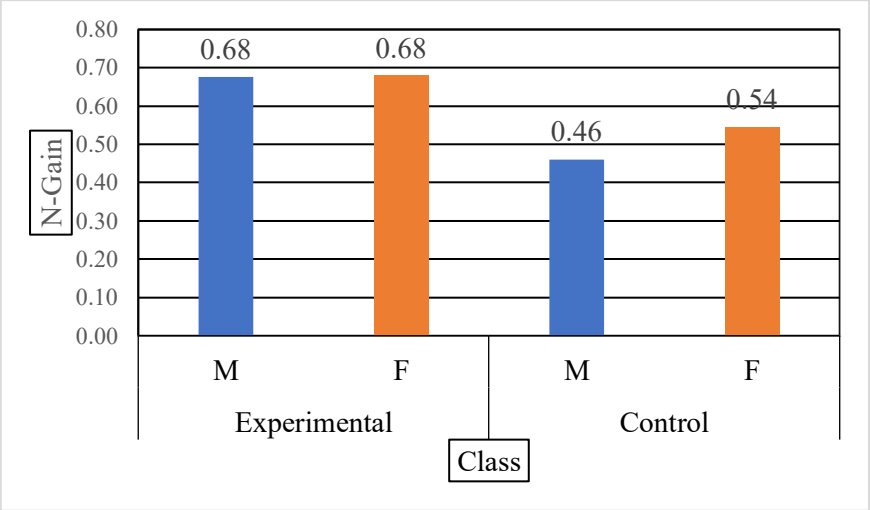


Fig.2. Students' scientific explanation ability based on gender across all indicators

Based on the data presented in Table 4 and Figure 2, the experimental group achieved identical mean N-gain scores for male and female students (0.68), both classified in the moderate category. In the control group, female students demonstrated a slightly higher mean N-gain (0.54) than male students (0.46), although both remained within the moderate category.

For the Reasoning indicator, female students in the experimental group achieved a higher N-gain (0.79, high category) than male students (0.68, moderate category). However, because this comparison was conducted descriptively and was not subjected to inferential statistical analysis, the observed difference should be interpreted with caution and should not be regarded as evidence of a gender effect. Future studies employing appropriate statistical procedures, such as a group-by-gender interaction analysis, are needed to determine whether gender moderates the effectiveness of the IoT-assisted SCBL model.

On the integrated Claim–Evidence–Reasoning (CER) indicator, both male and female students in the experimental group achieved the same high N-gain value (0.71). In contrast, lower gains were observed in the control group for both male (0.27) and female (0.39) students. This descriptive pattern suggests that the integration of SCBL with IoT technology provided male and female students with comparable opportunities to utilize authentic environmental data in constructing scientific explanations. Nevertheless, this interpretation remains exploratory because no statistical comparison between gender groups was performed (Bu'u, 2023; McNeill & Krajcik, 2012).

The only indicator for which the control group showed a marginally higher N-gain than the experimental group was Evidence among male students (0.71 versus 0.70). Given the negligible difference, this result is unlikely to have practical significance. Overall, the descriptive findings indicate that the IoT-assisted SCBL model produced broadly comparable improvements in scientific explanation ability for both male and female students. However, this conclusion should be interpreted cautiously and verified through inferential statistical analyses in future research.

Students' Response to the Implementation of the IoT-Assisted SCBL Model in the Water Pollution Topic

Students' responses to the IoT-assisted Sociobiological Case-Based Learning (SCBL) model were assessed using a 16-item questionnaire covering students' interest, conceptual understanding, comprehension of IoT-generated data, learning engagement, scientific explanation ability. Overall, students responded very positively to the learning model, with 45% of respondents categorized as Excellent and 53% as Good, indicating that 98% of students expressed positive perceptions of the implementation (Figure 3). These findings suggest that the IoT-assisted SCBL model was well accepted by students and successfully created a learning environment that supported active engagement with authentic socio-biological cases and real-time environmental data. Similar findings were reported by Pratiwi & Suwono (2016), who found that students' responses to the SCBL model reached an average of 81%, categorized as Excellent. Nevertheless, these questionnaire results should be interpreted as implementation-support evidence reflecting students' perceptions of the learning experience rather than as direct evidence of the model's effectiveness in improving scientific explanation ability.

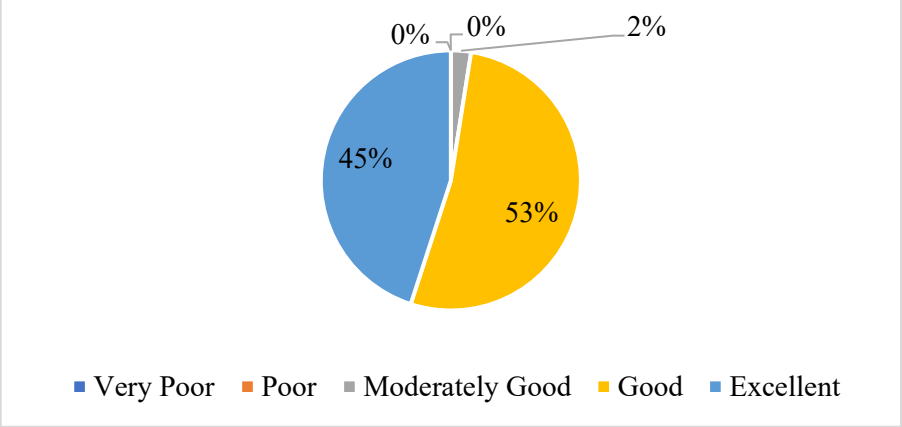


Fig.3. Percentage of response categories toward the implementation of the IoT-assisted SCBL model

Student Observation Sheet

Learning implementation was also evaluated using an observation sheet across the five SCBL stages, summarized in Table 5.

Table 5. Student Observation Sheet Results

No.	SCBL Learning Stage	Percentage (%)	Category
1	Orienting Students Toward the Sociobiological Problem	83,33	Excellent
2	Organizing Students to Plan Problem-Solving Strategies	83,33	Excellent
3	Group Investigation or Inquiry	83,33	Excellent
4	Developing and Presenting Inquiry Results	83,33	Excellent
5	Analyzing and Evaluating the Problem-Solving Process	66,67	Good

Notes: Categories follow (Widoyoko, 2009): Excellent (81–100%), Good (61–80%).

The implementation of the IoT-assisted Sociobiological Case-Based Learning (SCBL) model was generally successful. The first four stages of SCBL were implemented with an Excellent level of fidelity (83.33%), whereas the fifth stage, analyzing and evaluating the problem-solving process, was rated Good (66.67%). This final stage is inherently the most cognitively demanding because it requires students to critically reflect on the entire inquiry process, synthesize findings from IoT-generated environmental data, and construct complete scientific explanations. Importantly, no stage was rated below the Good category according to Widoyoko (2009), indicating that the instructional procedures were implemented consistently. Consequently, the observed differences in students' N-gain scores are likely attributable to the instructional intervention rather than to variations in implementation quality.

Overall, the findings suggest that integrating SCBL with IoT technology offers a pedagogical contribution beyond that of either component alone. SCBL provides an authentic sociobiological case-based learning framework that promotes inquiry, discussion, and evidence-based reasoning, whereas IoT supplies valid, real-time environmental data that strengthen students' use of empirical evidence in constructing scientific explanations. This integrated approach extends previous studies on SCBL, which did not incorporate real-time sensor data (Suwono et al., 2017; Wanloh & Nuangchalerm, 2022), as well as prior research on IoT in science education, which generally applied IoT as a technological tool without embedding it within an authentic sociobiological case-based learning framework (Ramlowat & Pattanayak, 2019). Nevertheless, because SCBL and IoT were implemented as a single instructional intervention, the individual contribution of each component could not be determined. Future research should therefore investigate the effectiveness of the integrated SCBL–IoT approach across different ecological topics, employ factorial or dismantling experimental designs to distinguish the effects of SCBL and IoT separately, and examine its impact on other higher-order learning outcomes, such as information literacy and problem-solving ability.

CONCLUSION AND SUGGESTION

This study concludes that the IoT-assisted Sociobiological Case-Based Learning (SCBL) model had a significant, though modest, effect on students' scientific explanation ability in the water pollution topic (Mann-Whitney U, Asymp. Sig. = 0.035; effect size r = 0.25), with the clearest gains occurring on the Reasoning and integrated CER components. Because the two groups differed significantly at pretest and the design did not separate the contributions of SCBL and IoT, these results are best read as evidence for the combined intervention rather than as a confirmed advantage for either component individually. The main contribution of this study is empirical: it demonstrates that pairing an authentic sociobiological case structure with real-time, sensor-derived evidence is a feasible and promising way to help students ground their scientific claims in valid data, rather than treating case-based reasoning and technology-based data collection as separate instructional strategies. Gender-based patterns observed in this study were descriptive rather than statistically confirmed and should be interpreted with caution pending further study.

For classroom practice, biology teachers seeking to apply this approach would need: access to low-cost IoT water-quality sensors, or feasible substitutes, capable of producing real-time readings; a locally relevant sociobiological case, such as a nearby polluted water source that can be visited or sampled within the school's schedule; and time within the lesson sequence for all five SCBL stages, from orienting students to the problem through to their reflection on the investigation process. Where dedicated IoT hardware is unavailable, teachers might adapt the model using shared low-cost sensor kits or portable water-testing devices to preserve the same authentic, evidence-based structure.

Future research is recommended to test the IoT-assisted SCBL model on other ecological topics and with larger and more diverse samples across different school contexts, to use a longer intervention duration, and to adopt a design, such as a factorial or dismantling design, capable of separating the individual contributions of the SCBL model and the IoT component.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS STATEMENT

Conceptualization, I.I. and J.R.; methodology, I.I. and J.R.; investigation, I.I.; data collection, I.I.; formal analysis, I.I.; data curation, I.I.; validation, J.R. and A.J.; writing—original draft preparation, I.I.; writing—review and editing, J.R. and A.J.; supervision, J.R. and A.J. All authors have read and approved the final version of the manuscript.

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DECLARATION OF GENERATIVE AI SOURCES

During the preparation of this manuscript, the authors used Grammarly for translation assistance and grammar checking. All generated content was carefully reviewed, revised, and verified by the authors, who take full responsibility for the final content of the manuscript.

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