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Development of Socio-Scientific Inquiry-Based Learning Worksheets on Coordination System Material to Improve Senior High School Students' Critical Thinking Skills

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Abstract: This study aims to develop and validate socio-scientific inquiry-based learning worksheets for the coordination system topic and to examine their effectiveness in enhancing senior high school students' critical thinking skills. The study involved 25 eleventh-grade students from SMA Swasta Harapan Paya Bakung and employed a Research and Development (R&D) approach based on the 4D model, combined with a One-Group Pretest–Posttest design. The quality of the developed worksheets was assessed through expert validation, while their practicality was evaluated based on teacher and student responses. The effectiveness of the worksheets was measured using critical thinking assessments developed according to Facione's indicators and analyzed using N-Gain scores. The results showed that the developed worksheets achieved a high level of validity, with validation scores exceeding 85%, and received positive responses from both teachers (94%) and students (90.6%). Furthermore, students demonstrated significant improvement in critical thinking skills, as indicated by an average posttest score of 90.72 and an N-Gain value of 0.85, which was categorized as high. These findings indicate that socio-scientific inquiry-based learning (SSIBL) worksheets serve as an effective learning resource for fostering critical thinking skills while promoting active, contextual, and meaningful biology learning experiences.

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Introduction

The rapid advancement of science and technology in the twenty-first century requires educational systems to equip students with competencies that enable them to respond effectively to increasingly complex and dynamic challenges. Among these competencies, critical thinking is widely recognized as a fundamental skill for twenty-first-century learning. Facione (2023) defines critical thinking as a deliberate and self-regulated process involving interpretation, analysis, evaluation, inference, and explanation. Through these processes, students are able to assess information critically, analyze arguments, and make informed decisions based on logical reasoning and evidence (Bahtiar et al., 2022). Consequently, fostering critical thinking has become one of the primary goals of modern education, as it prepares learners to adapt to scientific and technological developments while addressing global challenges (Fajari et al., 2020). Furthermore, critical thinking skills play an essential role in improving the quality of human resources and preparing future generations to face social, scientific, and technological challenges in an increasingly competitive global environment (Syafitri et al., 2021).

However, the development of critical thinking skills remains insufficiently emphasized in Indonesian education, as reflected in students' low performance across key

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indicators, including interpretation, analysis, evaluation, inference, explanation, and self-regulation (Hatria et al., 2024). Similarly, Fitriani et al. (2022) found that senior high school students in Bengkulu demonstrated low critical thinking skills, particularly in analysis, evaluation, and inference, while Hidayati et al. (2019) reported that several dimensions of critical thinking had not developed optimally. These findings are supported by Indonesia's performance in the 2022 PISA assessment, ranking 59th in reading literacy, 67th in mathematics, and 65th in science among 81 participating countries (Solihin et al., 2024). This condition is concerning because critical thinking is essential for addressing global challenges and enhancing the quality of future human resources (Syafitri et al., 2021).

The low level of students' critical thinking skills remains a major challenge in biology education, as many students experience difficulties in analyzing information, evaluating arguments, and solving contextual problems (Afifah et al., 2025). This condition is associated with teacher-centered and memorization-oriented learning practices that provide limited opportunities for developing higher-order thinking skills (Zubaidah, 2015). In addition, assessments predominantly emphasize lower-order cognitive skills, while tasks requiring analysis, evaluation, and problem-solving are less frequently implemented and often result in low achievement (Elvina, 2025). Limited learning motivation, participation in discussions, inquiry-based learning resources, and supportive classroom environments further hinder the development of critical thinking skills (Masdoeki, 2022). As a rational thinking process used to make decisions, critical thinking should be developed through meaningful learning experiences (Lestari et al., 2020).

According to Purwandari et al. (2024), socio-scientific issues (SSI) are scientific and social problems that require evidence-based decision-making because they affect everyday life and public interests. SSI involves complex, open-ended issues linked to scientific concepts and procedures (Zeidler, 2009; Badeo et al., 2022), such as smoking, electronic cigarettes, and air pollution in respiratory system learning. Integrating SSI into education connects biological concepts with social contexts, creating meaningful learning experiences while encouraging scientific thinking, informed decision-making, and problem-solving (Subiantoro, 2017; Amos et al., 2020). Socio-Scientific Inquiry-Based Learning (SSIBL) integrates SSI with scientific inquiry and has been shown to effectively promote critical thinking skills (Amos et al., 2020). According to Knippels (2018), SSIBL engages students in examining socio-scientific dilemmas through questioning, inquiry, evidence analysis, argumentative discussion, decision-making, and reflection, thereby fostering scientific literacy, democratic citizenship, and critical thinking (Subiantoro, 2017; Zeidler, 2009).

Numerous studies have shown that Socio-Scientific Inquiry/Issues (SSI)-based learning effectively enhances scientific literacy, critical thinking, and conceptual understanding by linking biology concepts to real-life problems. However, its implementation remains limited due to the lack of Student Worksheets (LKPD) specifically designed to guide students through inquiry and socio-scientific decision-making processes (Miftahuddin et al., 2024). Previous studies reported that SSIBL improved students' problem-solving abilities (Pulungan et al., 2025) and critical thinking skills (Fadhillah et al., 2025), yet the development of SSIBL-based worksheets is still restricted to certain topics and contexts. Therefore, further research is needed to apply SSIBL-based worksheets to other biology materials and broaden evidence of their effectiveness in senior high school biology learning.

The low performance of students' critical thinking skills remains a challenge in biology education, particularly in analysis and evaluation indicators, which have been reported to be below 50% (Putri et al., 2024). Although Student Worksheets (LKPD) support

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learning and critical thinking development, SSIBL-based worksheets remain limited in schools (Firtsanianta et al., 2022). In addition, digital resources such as e-books and e-modules are increasingly used in biology education but generally focus on content delivery without integrating the SSIBL approach (Rahmawati, 2022). Previous studies have examined learning models and media separately rather than developing worksheets that systematically foster critical thinking and evidence-based decision-making (Putri et al., 2024). Furthermore, research on SSIBL-based worksheets for complex biology topics, such as the coordination system in private senior high schools, remains limited.

These conditions highlight the need for SSIBL-based Student Worksheets (LKPD) as contextual learning resources to enhance critical thinking skills. Therefore, This study aims to develop and validate socio-scientific inquiry-based learning worksheets for the coordination system material and to examine their effectiveness in enhancing senior high school students' critical thinking skills. The findings are expected to support the implementation of SSIBL and provide innovative learning resources for biology teachers in addressing 21st-century learning challenges.

Research Method

This study employed a Research and Development (R&D) approach using the 4D (Four-D Model) development model proposed by Thiagarajan (1974) (Puspitasari et al., 2020). This model consists of four stages: (1) Define, (2) Design, (3) Develop, and (4) Disseminate. The design of the 4D (Four-D Model) can be seen in Figure 1.

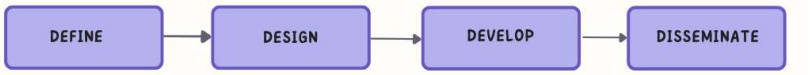

Figure 1. The Design of the 4D Model (Thiagarajan, 1974)

The study was conducted following the four-phase development procedure formulated by Thiagarajan (1974). This approach guided both the creation of the SSIBL-based Student Worksheet (LKPD) and the assessment of learners' critical thinking abilities. Figure 1 presents the flow of the development process, whereas Table 1 provides an overview of the activities and instruments employed throughout the study.

Table 1. Stages of the 4D Development Model

Stages	Description of Activities
Define	Conducted front-end, student, curriculum, concept, and task analyses to identify learning needs and formulate objectives. Critical thinking indicators were adapted from Facione's framework, and data were collected through teacher interviews and questionnaires.
Design	Designed SSIBL-based worksheets by formulating objectives, selecting materials and socio-scientific issues, developing learning activities, and preparing critical thinking instruments, resulting in storyboards and an initial draft.
Develop	Developed and validated the worksheets and instruments through expert review, revised the product, and conducted testing to evaluate students' critical thinking skills.
Disseminate	Implemented and disseminated the validated worksheets through learning activities, socialization, and publication, while collecting feedback for broader implementation.

This Research and Development (R&D) study employed Thiagarajan's 4D model and a One-Group Pretest–Posttest Design involving 25 eleventh-grade students of SMA Swasta Harapan Paya Bakung. Permission was obtained from the school principal, and participants were informed about the study, participated voluntarily, and were assured of confidentiality and anonymity. The instruments included validity, practicality, and effectiveness assessments. Validation sheets completed by media and material experts evaluated the

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content, presentation, and integration of critical thinking indicators in the SSIBL-based worksheets. Practicality was assessed through questionnaires administered to one biology teacher and 25 students, while effectiveness was measured using a critical thinking test consisting of six essay questions based on Facione's indicators. The test instrument is presented in Table 2.

Table 2. Blueprint of the Critical Thinking Test Instrument

No.	Learning Objectives	Critical Thinking Indicators	Question Description
1)	Students identify neuron structures through images, models, or cases and relate them to nervous system disorders in SSIBL contexts.	Interpretation	Students explain the relationship between adolescent insomnia caused by gadget use and coordination system disorders by describing the roles of the nervous, hormonal, and sensory systems.
2)	Students describe nerve impulses, voluntary and reflex movements, and the central and peripheral nervous systems through observations or case studies.	Analysis	Students analyze the effects of nighttime gadget exposure by tracing nerve impulse pathways and relating neuron functions to sleep difficulties.
3)	Within the SSIBL learning process, students critically evaluate how behavioral and lifestyle factors can influence the development of neurological disorders.	Inference	Students draw conclusions about the long-term effects of melatonin production disorders caused by late-night sleeping habits.
4)	Students analyze relationships between hormonal system structures and functions based on data or cases.	Evaluation	Students evaluate the impact of late-night sleeping habits on hormonal balance and adolescent sleep disorders based on melatonin and pineal gland functions.
5)	Students present analyses of lifestyle-related hormonal disorders based on scientific studies and SSIBL.	Explanation	Students explain how excessive gadget use and sleep deprivation affect hormonal and sensory system functions, contributing to insomnia.
6)	Students evaluate the effects of lifestyle patterns on sensory system disorders through SSIBL.	Self-Regulation	Students reflect on their gadget use habits and propose preventive measures against insomnia based on coordination system concepts.

Data for this study were generated from multiple sources. Quantitative evidence regarding students' critical thinking abilities was collected through assessment tests, while qualitative information was derived from expert reviews and feedback questionnaires completed by teachers and students.

$$\text{Percentage of validity} = \frac{Obtained\ score}{Maximum\ score} \times 100\% \ldots. \text{(Formula 1)}$$

Table 3. Validity Criteria of the Student Worksheet

Percentage	Validity Criteria	Description
0% – 44%	Invalid	Requires total revision
45% – 64%	Less Valid	Requires major revisions
65% – 84%	Valid	Requires minor revisions
85% – 100%	Very Valid	No revision required

Source: (Nayla, 2025)

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$$S = \frac{\sum p}{\sum n} \text{ ..... (Formula 2)}$$

S = Score per aspect
∑p = Total score per aspect from all students
∑n = Number of students

The validity analysis focused on the worksheets developed in this study. If the results of expert validation met the validity criteria, the worksheets were considered valid.

Table 4. Practicality Criteria of the Student Worksheet

Percentage	Description
0% – 20%	Very Impractical
21% – 40%	Impractical
41% – 60%	Fairly Practical
61% – 80%	Practical
81% – 100%	Very Practical

Source: (Muslimah et al., 2021)

$$\text{N-Gain} = \frac{Score\ \ pre\ test - score\ post\ test}{Score\ \ maximum - score\ pre\ test} \text{ …..(Formula 3)}$$

Table 5. N-Gain Classification of Worksheet Effectiveness

N-Gain Score	Classification	Description
N-Gain ≥ 0.7	High	Effective
0.3 ≤ N-Gain < 0.7	Moderate	Moderately Effective
N-Gain < 0.3	Low	Ineffective

Source: (Dwi, 2023)

The effectiveness analysis was based on pre-test and post-test learning outcomes. Worksheet effectiveness was evaluated using N-Gain scores, while normality testing and the Wilcoxon test were used to determine the significance of score differences.

Results and Discussion

Define Phase

The define stage, the first phase of the development research, aimed to identify learning needs and challenges for developing SSIBL-based worksheets on the coordination system. This stage included front-end, learner, concept, and task analyses, as well as the formulation of learning objectives. The results guided the development of instructional media aligned with curriculum requirements and student characteristics. The findings of the define stage are presented in Table 6.

Table 6. Results of the Define Stage Analysis at SMA Swasta Harapan Paya Bakung

Component	Results
Front-End Analysis	Learning remains teacher-centered, with limited use of learning media and low teacher familiarity with SSIBL, resulting in low student engagement and critical thinking skills. Teachers showed interest in implementing SSIBL-based worksheets after introduction.
Learner Analysis	Students have low prior knowledge of the coordination system, tend to be passive, and experience difficulty relating concepts to daily life. They showed positive responses to SSIBL-based worksheets.
Concept Analysis	The coordination system topic (nervous system, hormones, and sensory organs) is complex and requires conceptual understanding connected to real-life issues, such as insomnia.
Task Analysis	Learning activities were designed to develop critical thinking through problem analysis, concept application, and evidence-based argumentation integrated into

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Component	Results
	worksheet activities.
Specifying Instructional Objectives	Learning objectives were formulated to enable students to identify, analyze, and evaluate coordination system concepts through SSIBL activities while developing evidence-based critical thinking skills.

Design Phase

Based on the define stage results, the researcher developed an SSIBL-based worksheet to enhance students' critical thinking skills in understanding the coordination system. The worksheet facilitates exploration of contextual issues, evaluation of different perspectives, and construction of scientific evidence-based arguments. The design stage addressed content structure, visual aspects, and the coherence of the worksheet's flow, using Canva with appropriate color combinations, a systematic layout, and clear, attractive information presentation.

Table 7. Presentation of Worksheets, Learning Activities, and Critical Thinking Indicators

Worksheet Presentation	Learning Activities	Critical Thinking Indicators
	The teacher presents everyday dilemmas, connects them to biology concepts, and stimulates students' curiosity through images, videos, or case stories.	Students interpret socio-scientific issues related to coordination system disorders by linking them to the concepts of the nervous, endocrine, and sensory systems.
	Students are asked to express their initial opinions individually or in groups without being judged as right or wrong in order to identify their prior knowledge and perspectives.	Students demonstrate inference skills by presenting initial opinions on issues related to human coordination system disorders logically based on prior knowledge and daily experiences.
	Students formulate questions (scientific, social, and personal) to understand the dilemma, then the teacher groups them according to learning objectives.	Students demonstrate analysis skills by formulating relevant scientific, social, and personal questions to understand the causes, impacts, and solutions of human coordination system disorder issues.
	Students conduct inquiry activities (literature study, observation, discussion, or experiments) to collect data supporting problem analysis.	Students evaluate information from various scientific sources to answer questions and relate them to the nervous, endocrine, and sensory systems.

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Worksheet Presentation	Learning Activities	Critical Thinking Indicators
	Students engage in discussions to clarify values, compare findings, and present evidence-based arguments while respecting differences of opinion.	Students explain inquiry results and arguments orally based on evidence and respond to others' opinions logically and respectfully.
	Students formulate solutions based on inquiry and discussion results that are applicable and encourage attitude or behavior change.	Students conclude and make rational decisions based on data analysis and discussion.
	Students reflect on the process and changes in understanding orally or in writing to develop metacognition.	Students reflect on their thinking process, changes in opinions, as well as strengths and weaknesses of their decisions (metacognition).

Development Phase

At the develop stage, the SSIBL-based worksheet was designed to engage students in analyzing socio-scientific issues through inquiry, data analysis, argument evaluation, and evidence-based decision-making. To ensure product quality, validation sheets, practicality questionnaires, and pre-test and post-test instruments were developed. Validation was conducted by three experts to evaluate visual design, content alignment with the Merdeka Curriculum, and SSIBL integration (Jayanti & Pertiwi, 2023). The results served as the basis for product revision before practicality and effectiveness testing, as presented in Table 8.

Table 8. Validation Results of Media, Material, and SSIBL

Expert	Assessed Aspect	Number of Items	Score	Maximum Score	Percentage (%)	Criteria
Media	Graphic Design	8	29	32	91%	Very Valid
	Material Presentation	8	29	32	91%	
	Average Score (%)				**91%**	
Material	Content Feasibility	7	27	28	96%	Very Valid
	Language	8	32	32	100%	
	Material Presentation	8	30	32	94%	
	Average Score (%)				**97%**	
SSIBL	Content Feasibility	3	10	12	83%	Very Valid
	Construction Feasibility	3	10	12	83%	

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Expert	Assessed Aspect	Number of Items	Score	Maximum Score	Percentage (%)	Criteria
	Language Feasibility	3	9	12	75%	
	Format & Appearance Suitability	2	8	8	100%	
	Average Score (%)				**85%**	

Based on Table 8, expert validation results indicated that the developed worksheet was highly valid and suitable for implementation after revision. Validation covered media, content, and SSIBL aspects. In the media aspect, graphic design and material presentation each obtained a score of 91%, resulting in an overall average of 91% in the highly valid category. These findings suggest that the worksheet was attractively designed and aligned with students' learning needs, consistent with Damayanti (2025), who reported that visual learning media enhance learning interest, participation, and understanding.

Each component of the material validation was assessed separately, with the language component receiving the highest score (100%), followed by content (96%) and material presentation (94%). The overall average score of 97% places the worksheet in the highly valid category. These results indicate that the worksheet presents material systematically, uses communicative language, and aligns with the learning objectives of the Merdeka Curriculum. This finding is consistent with Sultan (2026), who reported that systematically designed interactive learning multimedia can improve students' conceptual understanding of complex topics by facilitating comprehension through structured and visually supported presentations.

Meanwhile, the SSIBL component was validated across content (83%), construction (83%), language (75%), and format and appearance (100%), resulting in an overall score of 85% in the highly valid category. These findings indicate that the worksheet effectively integrates SSIBL by facilitating scientific inquiry and critical analysis of socio-scientific issues, consistent with Irawati and Wulandari (2026). Overall, the worksheet met the pedagogical, visual, and scientific standards required for SSIBL implementation, providing a basis for practicality and effectiveness testing. Practicality was subsequently assessed through teacher and student response questionnaires, with the results presented in Table 9.

Table 9. Results of the Student and Teacher Practicality Test

Respondents	Number of Items	Obtained Score	Maximum Score	Percentage (%)	Category
Students (n = 10)	23	86.4	92	94%	Highly Practical
Teachers (n = 2)	12	43.5	48	90%	Highly Practical

Based on Table 9, student and teacher responses indicate that the developed worksheet is highly practical, with scores of 94% and 90%, respectively. Students highlighted its visual design and ease of use, while teachers emphasized its clear instructions, structured activities, and integration of scientific concepts with real-life contexts. The worksheet also promoted active participation and critical thinking, consistent with Melati et al. (2025), who reported that socio-scientific issues-based learning materials enhance scientific argumentation, logical reasoning, and evidence-based decision-making. Therefore, the worksheet is practical, feasible, and pedagogically relevant, providing a basis for effectiveness testing, the results of which are presented in Table 10.

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Table 10. Effectiveness Test Results of the Developed Worksheet Based on N-Gain Analysis

Evaluation	Mean Score	Maximum Score	N-Gain Score	Category
Pre-test (n = 25)	37.48	100	0.85	High/Effective
Post-test (n = 25)	90.72	100		

The purpose of the efficacy evaluation was to ascertain how much the Socio-Scientific Inquiry-Based Learning (SSIBL) worksheet enhanced students' critical thinking abilities after the learning process. The mean pre-test score was 37.48, whereas the mean post-test score rose to 90.72, according to the N-Gain formula analysis of the pre-test and post-test results. The computed N-Gain value, which is in the upper range, was 0.85. This finding suggests that the created worksheet improved students' critical thinking abilities and learning outcomes. Additionally, the test scores for each critical thinking indication were used to illustrate the data. The six essential elements of critical thinking abilities are interpretation, analysis, evaluation, inference, explanation, and self-regulation. Table 11 displays the outcomes for each component.

Table 11. Results of Critical Thinking Skills Assessment by Indicator

Critical Thinking Skill Aspect	N-Gain Score	Category
Interpretation	0.91	High/Effective
Analysis	0.85	High/Effective
Evaluation	0.88	High/Effective
Inference	0.94	High/Effective
Explanation	0.89	High/Effective
Self-Regulation	0.92	High/Effective

As shown in Table 11, all critical thinking indicators achieved high N-Gain scores, indicating the effectiveness of the learning approach in enhancing students' critical thinking skills. The highest gain was observed in inference (0.94), followed by self-regulation (0.92), interpretation (0.91), explanation (0.89), evaluation (0.88), and analysis (0.85). These results demonstrate substantial improvement in students' ability to understand problems, analyze information, evaluate evidence, draw conclusions, justify arguments, and reflect on their thinking processes.

Using SPSS software, a Wilcoxon Signed-Rank Test was performed to support these conclusions. Based on the findings of the post-test normalcy analysis and the comparison of the pre-test and post-test scores, the Wilcoxon test was chosen. With a sample size of 25, normality testing using the Kolmogorov–Smirnov and Shapiro–Wilk approaches produced significance values (Sig.) of 0.000 and 0.001, respectively. The null hypothesis that the data were normally distributed was rejected since the significance values for both tests were less than 0.05 ($p < 0.05$). In order to determine whether there was a significant difference between the pre-test and post-test scores, the non-parametric Wilcoxon Signed-Rank Test was utilized. Table 12 displays the analysis's findings.

Table 12. Wilcoxon Signed-Rank Test Results

	Pre-test – Post-test
Z	-4.380[b]
Asymp. Sig. (2-tailed)	0.000

The Wilcoxon Signed-Rank Test analysis yielded a Z value of -4.380 and a significance value (Asymp. Sig. 2-tailed) of 0.000, both of which are significantly below the significance level of 0.05. This finding shows that the pre-test and post-test scores after the learning intervention was put into place differed statistically significantly. The post-test results were often greater than the pre-test results, according to the negative Z value. The N-

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Gain score of 0.85, which is in the upper range and indicates a significant improvement in pupils' skills, lends more credence to these conclusions. As a result, the N-Gain analysis and the Wilcoxon test findings consistently show that the adopted learning strategy significantly improved students' learning outcomes. Consequently, the observed improvements can be directly attributed to the structured instructional intervention employed in this study.

The improvement in students' critical thinking skills can be attributed to the stages of Socio-Scientific Inquiry-Based Learning (SSIBL), which systematically develop Facione's critical thinking indicators. In the initial stage, students analyzed socio-scientific issues related to excessive gadget use and insomnia, enabling them to connect concepts of the nervous, hormonal, and sensory systems with real-life situations and develop interpretation skills. This finding is consistent with Knippels (2018), who emphasized the role of socio-scientific issue exploration in building awareness of real-world problems, and Rahmawati (2020), who reported that contextual problems enhance interpretation skills and meaningful learning of scientific concepts.

Based on the N-Gain analysis, all critical thinking indicators proposed by Facione improved within the high category following the implementation of the SSIBL-based worksheets, including Interpretation (0.91), Analysis (0.85), Inference (0.88), Evaluation (0.94), Explanation (0.89), and Self-Regulation (0.92). These results indicate that the worksheets effectively supported the development of students' critical thinking skills across all dimensions, with Evaluation showing the highest improvement and Analysis the lowest.

The interpretation indicator achieved an N-Gain score of 0.91, indicating high improvement in understanding and interpreting scientific phenomena through the analysis of socio-scientific issues related to excessive gadget use and insomnia (Knippels, 2018). Analysis obtained the lowest N-Gain score (0.85), although it remained in the high category, likely due to the complexity of examining relationships among ideas and multiple perspectives (Facione, 2023). However, SSIBL activities such as question formulation and investigation supported the development of this skill (Amos et al., 2020). Inference achieved an N-Gain score of 0.88, reflecting improved ability to draw evidence-based conclusions (Facione, 2023), while Evaluation showed the highest gain (0.94), indicating substantial improvement in assessing information credibility and evidence (Melati et al., 2025). Explanation achieved an N-Gain score of 0.89 through discussions and presentations that strengthened students' ability to justify conclusions (Zeidler, 2009). Self-regulation achieved the second-highest gain (0.92), as reflection activities encouraged students to monitor their thinking and evaluate decisions (Maksum et al., 2021). Overall, all six indicators achieved high N-Gain scores, demonstrating the effectiveness of SSIBL-based worksheets in enhancing critical thinking skills.

Conclusion

Based on the findings, the SSIBL-based Student Worksheet (LKPD) on the coordination system met the criteria of validity, practicality, and effectiveness for senior high school biology learning. These results indicate that the objective of developing instructional materials to enhance students' critical thinking skills was achieved. The worksheet also promoted meaningful, student-centered learning by engaging students in exploring scientific concepts through relevant real-life issues.

The improvement in students' critical thinking skills can be attributed to the SSIBL approach, which encourages students to interpret and analyze socio-scientific issues, gather and evaluate evidence, and engage in evidence-based discussions and reflective decision-

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making. These learning experiences fostered the development of interpretation, analysis, evaluation, inference, explanation, and self-regulation skills. Therefore, SSIBL-based worksheets have strong potential to support student-centered biology learning and higher-order thinking skills. Future studies are recommended to apply this approach to other biology topics and examine its effects on additional 21st-century competencies, including creativity, communication, collaboration, and problem-solving.

Recommendation

Based on the findings, biology teachers are encouraged to implement SSIBL-based worksheets to enhance critical thinking skills through discussion, evidence evaluation, and reflection. Schools should support implementation through professional development, learning resources, and student-centered policies. Curriculum developers are advised to integrate socio-scientific issues and inquiry-based activities into instructional materials. Future research should examine the effectiveness of SSIBL-based worksheets across various topics, educational levels, and learning contexts, as well as their impact on critical thinking, scientific literacy, and decision-making skills.

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