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Structured Inquiry Learning: Enhancing Critical Thinking and Conceptual Understanding through Productive Questioning

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ABSTRACT

Purpose of the study: This study aims to examine the effect of structured inquiry learning based on productive questioning on students' critical thinking skills and conceptual understanding of plant tissue structure in senior high school biology learning.

Methodology: This study employed a quantitative quasi-experimental method using a non-equivalent control group design. Data were collected using critical thinking and conceptual understanding tests, observation sheets, and documentation. Statistical analyses included descriptive statistics, Kolmogorov–Smirnov normality test, Levene's homogeneity test, N-gain analysis, independent sample t-test, and effect size calculation using SPSS software.

Main Findings: The results showed significant differences between experimental and control groups in critical thinking and conceptual understanding. The experimental group achieved higher posttest scores, moderate-to-high N-gain values, and large effect sizes. These findings indicate that structured inquiry learning with productive questioning effectively improves students' higher-order thinking and conceptual mastery.

Novelty/Originality of this study: This study integrates productive questioning explicitly within a structured inquiry learning model and examines its simultaneous effect on critical thinking and conceptual understanding. This approach provides new empirical evidence on how productive questioning strengthens cognitive engagement and enhances learning outcomes in biology education contexts.

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1. INTRODUCTION

21st-century education demands the development of higher-order thinking skills, particularly critical thinking and conceptual understanding, as core competencies for students. These skills are essential for facing the complexities of science and modern global challenges [1], [2]. Science learning no longer focuses on memorizing facts, but rather on the active process of analyzing, evaluating, and constructing knowledge [3], [4]. International reports such as the PISA (Philosophy of Science and Mathematics) indicate that students' scientific literacy achievements remain low, particularly in scientific reasoning [5], [6]. This situation demonstrates the need for a transformation in learning strategies that place greater emphasis on developing higher-order thinking skills [7].

Plant tissue structure is a topic in biology that is abstract and microscopic. Understanding this material requires the ability to conceptually relate cell structure to its physiological function [8], [9]. However, school learning is still dominated by a teacher-centered approach with memorization-oriented questions. As a result, students struggle to explain the relationships between tissues scientifically. This situation impacts students' critical thinking skills and conceptual understanding.

The structured inquiry learning model provides a systematic framework for students to observe, investigate, and draw conclusions based on empirical data. This model places students at the center of learning, with focused teacher guidance [10], [11]. Research shows that structured inquiry is effective in improving conceptual understanding and critical thinking skills [12]-[14]. However, the success of this model is greatly influenced by the quality of the cognitive interactions established during learning. One key factor in these interactions is the quality of the questions used by the teacher [15]-[17].

Productive questions encourage students to analyze, evaluate, and construct in-depth understanding. These questions focus not on a single answer, but on the scientific thinking process. In inquiry-based learning, productive questions serve as cognitive scaffolding that guides concept exploration [18]-[20]. Research shows that higher-order questions can improve students' reasoning and conceptual understanding. Therefore, integrating productive questions is an essential component of inquiry-based science learning.

Although numerous studies have demonstrated that inquiry-based learning models can improve students' critical thinking skills and conceptual understanding, studies specifically incorporating productive questions within structured inquiry models are limited. For example, a meta-analysis concluded that inquiry-based learning is effective in improving students' critical thinking skills, but highlighted the need for a more systematic approach to evaluating specific pedagogical variables such as questioning strategies [21]. Other studies evaluating inquiry approaches to science learning have shown that these models promote engagement and the development of scientific communication skills, but have not explicitly examined the role of productive inquiry in the context of enhancing conceptual understanding or critical thinking [22]. Other relevant research also confirms that the main focus of inquiry-based learning is to encourage students to actively explore and construct their own scientific understanding, but the analysis is still more general regarding scientific skills in general, without analyzing the types of questions used and how the quality of these questions affects students' conceptual understanding and critical thinking specifically [23]. On the other hand, research by Aido [24], stated that the style and structure of teacher questioning during inquiry activities significantly influence higher-order thinking. However, these studies were qualitative in nature and did not include empirical evaluations of the effect of productive questioning on the understanding of specific concepts, such as plant tissue structure. Thus, a clear research gap exists: although inquiry-based learning has been shown to have a positive effect on students' critical thinking skills, the specific role of productive questioning as a pedagogical variable that facilitates critical thinking and conceptual understanding has not been widely studied empirically, especially in complex biology materials such as plant tissue structure.

The novelty of this research lies in the systematic integration of productive questioning and a structured inquiry learning model. This study not only measures learning outcomes but also analyzes the impact of productive questioning on two key cognitive aspects simultaneously. The focus on plant tissue structure provides a contextual contribution rarely studied before. Furthermore, this study positions productive questioning as a primary pedagogical variable, not merely a supporting strategy. Thus, this research offers a new perspective on the development of inquiry-based biology learning.

Based on these issues, this research is crucial for improving the quality of biology learning in schools. This study aims to analyze the effect of implementing productive questioning in a structured inquiry learning model on students' critical thinking skills. Furthermore, this research also aims to examine its influence on understanding the concept of plant tissue structure. The results are expected to provide theoretical and practical contributions to the development of science learning strategies. These findings are also expected to serve as a reference for teachers and researchers in designing more meaningful learning..

2. RESEARCH METHOD

This study employed a quantitative approach with a quasi-experimental approach. The research design employed a non-equivalent control group design, as full subject randomization was not possible [25], [26]. This design was chosen to compare the effect of implementing productive questions within a structured inquiry learning model on students' critical thinking skills and conceptual understanding. In general, the research design can be described as follows:

Table 1. Research Design

Group	Pretest	Treatment	Posttest
Experiment	O_1	X	O_2
Control	O_1	–	O_2

The population in this study were all eleventh-grade students of a state senior high school in Betung sub-district, South Sumatra, who were studying plant tissue structure in the even semester of the current academic year. The research sample was taken using a purposive sampling technique, taking into account the equality of academic ability and class characteristics. Two classes were selected as research samples, namely one class as an experimental class and one class as a control class, each consisting of 30 students. The experimental class was given structured inquiry learning based on productive questions, while the control class used conventional teacher-centered learning.

Data collection techniques in this study were conducted through several methods. First, a written test was used to measure students' critical thinking skills and conceptual understanding, both before and after the learning treatment. Second, an observation sheet was used to observe the implementation of the learning process and the level of student engagement during the application of the inquiry learning model. Third, documentation was used as supporting data, including teaching modules and student worksheets, as well as student work relevant to the research objectives.

The research instruments included a critical thinking test instrument designed based on critical thinking indicators adapted from Peter and Gittens [27], including interpretation, analysis, inference, evaluation, and explanation. The questions were in the form of reasoned multiple-choice questions and short essay questions. The conceptual understanding instrument was designed based on conceptual understanding indicators, including the ability to explain, classify, provide examples, and relate concepts to plant tissue structure.

Table 2. Research instrument grid

Variable	Indicators	Question Format	Number of Questions
Critical Thinking	Interpreting concepts	Multiple Choice with Reasoning	5
	Analyzing structure-function relationships	Description	5
	Evaluating scientific arguments	Description	5
Concept Understanding	Identifying tissue structures	Multiple Choice	5
	Explaining tissue functions	Description	5
	Relating structure and function	Multiple Choice	5

The validity test results indicated that all instrument items were valid, with the Product Moment correlation coefficient ranging from r = 0.42–0.81, higher than the table r value (0.361). Reliability testing using Cronbach's Alpha yielded an α value of 0.87, indicating that the instrument has a high level of reliability and is suitable for use in research.

Data analysis was conducted quantitatively using SPSS software with a significance level of $\alpha = 0.05$. The initial stage of the analysis included the Kolmogorov–Smirnov normality test and Levene's homogeneity test to ensure the data met the assumptions of parametric analysis [28], [29]. Next, improvements in critical thinking skills and conceptual understanding were analyzed using normalized gain (N-gain). Hypothesis testing was conducted using an independent sample t-test with the decision-making criterion: H_0 is rejected if the significance value (p-value) is <0.05. The magnitude of the treatment effect was analyzed using effect size (Cohen's d) to determine the effectiveness of the treatment.

3. RESULTS AND DISCUSSION

The results of the descriptive statistical analysis indicate differences in critical thinking skills and conceptual understanding between the experimental and control classes. Data were obtained from the results of pretests and posttests given to both groups before and after treatment. Table 3 presents a summary of the descriptive statistics for the pretest and posttest scores of students' critical thinking skills and conceptual understanding.

Table 3. Descriptive Statistics of Pretest and Posttest Scores

Variable	Group	N	Mean Pretest	SD Pretest	Mean Posttest	SD Posttest
Critical Thinking	Experimental	30	52.47	7.86	82.13	6.94
	Control	30	51.90	8.02	71.45	7.21
Concept Understanding	Experimental	30	54.10	7.45	84.27	6.38
	Control	30	53.87	7.61	73.06	6.89

Table 3 shows that the average pretest scores for both groups were relatively equal, indicating comparable initial student abilities. However, after treatment, the experimental class showed a higher increase in scores than the control class in both critical thinking skills and conceptual understanding. The Kolmogorov–Smirnov normality test showed that all pretest and posttest data in both groups were normally distributed (p >

0.05). Furthermore, the homogeneity of variance test using Levene's Test showed a significance value > 0.05, indicating that the data had homogeneous variance. Thus, the data met the assumptions for parametric statistical testing.

To determine the improvement in student learning outcomes, the normalized gain (N-gain) value was calculated. The results of the analysis are presented in Table 4.

Table 4. Average N-Gain of Critical Thinking Ability and Conceptual Understanding

Variable	Group	N-Gain (Mean)	Category
Critical Thinking	Experimental	0.63	Medium–High
	Control	0.39	Medium
Concept Understanding	Experimental	0.68	High
	Control	0.42	Medium

These results indicate that students in the experimental class improved their critical thinking skills and conceptual understanding significantly compared to the control class, with moderate to high improvement.

Hypothesis testing was conducted using an independent sample t-test to determine differences in critical thinking skills and conceptual understanding between the experimental and control classes. The results are presented in Table 5. The hypothesis testing was conducted to determine differences in critical thinking skills and conceptual understanding between students participating in structured inquiry learning based on productive questions (the experimental class) and students participating in conventional learning (the control class). The testing was conducted using an independent sample t-test with a significance level of α = 0.05.

Table 5. Hypothesis Test Results (Independent Sample t-test)

Variable	Sig. (p-value)	Decision	Description
Critical Thinking	0.000	H_0 rejected	There is a significant difference
Conceptual Understanding	0.000	H_0 rejected	There is a significant difference

Visualization of the effect size analysis results shows that the application of productive questions in the structured inquiry learning model has a significant impact on students' critical thinking skills and conceptual understanding. The effect size value for critical thinking skills is d = 0.89, while for conceptual understanding it is d = 0.93. Based on Cohen's criteria, both values fall into the large effect category, indicating that the treatment given has a strong impact on improving both variables.

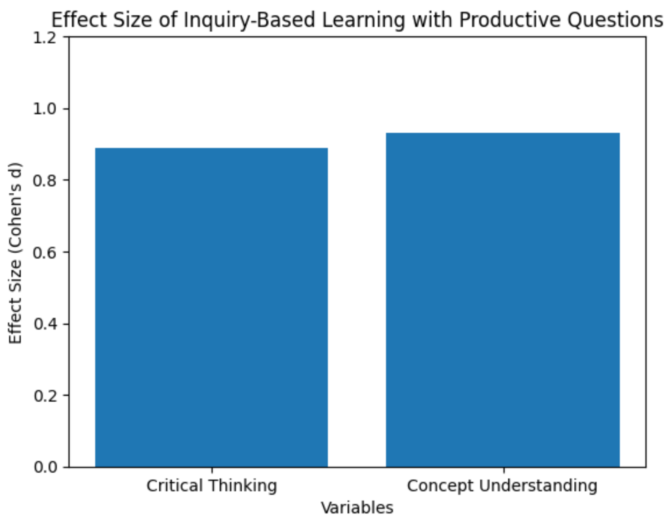

Figure 1. Visualization of Effect Size (Cohen’s d)

The results of the study indicate that the implementation of structured inquiry learning based on productive questions had a positive impact on improving students' critical thinking skills and conceptual understanding. This is evident from the difference in average posttest scores between the experimental and control classes, with the experimental class achieving higher scores on both variables. Furthermore, the N-gain value in the experimental class was in the moderate to high category, while the control class was only in the moderate category. These findings indicate that learning that emphasizes active student involvement through productive questions can encourage higher-order thinking processes and deeper conceptual understanding. The statistical test results, which showed a significant difference ($p < 0.05$) and a large effect size ($d > 0.8$), further confirm that the treatment provided had a strong and meaningful influence on student learning outcomes.

These findings align with previous research that found inquiry-based learning models to be effective in improving students' critical thinking skills and conceptual understanding. Research by Van Uum et al. [30] showed that an inquiry-based learning approach significantly improves critical thinking skills because it encourages students to ask questions, analyze information, and draw conclusions based on a systematic investigative process. Similar results were also found by Mediana Jr. et al. [13] who reported that inquiry learning positively contributes to students' conceptual understanding because it allows them to construct knowledge through direct experience and conceptual reflection. Furthermore, other research shows that the application of structured inquiry can significantly improve critical thinking skills due to the systematic and directed learning stages, especially when combined with questions that stimulate higher-order thinking processes [31].

The novelty of this research lies in the explicit integration of productive questions into a structured inquiry learning model and the measurement of their impact on two cognitive aspects simultaneously: critical thinking skills and conceptual understanding. Unlike some previous studies that only emphasize one aspect of learning outcomes, this study demonstrates that productive questions not only strengthen higher-order thinking processes but also help students develop a more comprehensive conceptual understanding. Furthermore, the use of effect size analysis provides a more comprehensive picture of the strength of the treatment's influence, making the findings not only statistically significant but also practically meaningful in the classroom context.

The implications of this research suggest that teachers need to systematically integrate productive questions into inquiry learning to enable students to be more active, reflective, and critical in constructing knowledge. This approach can also serve as a basis for developing learning tools, such as modules, student worksheets, and evaluation instruments oriented toward strengthening higher-order thinking skills. Furthermore, the results of this study can serve as a reference for educational policymakers in designing learning strategies that align with the demands of strengthening 21st-century competencies. However, this study has several limitations, including the limited sample size within a single school context, which limits the generalizability of the results. Furthermore, this study did not consider other factors such as learning motivation, learning styles, and differences in students' initial abilities in greater depth. Therefore, future research is recommended to involve a larger sample size, a longer treatment duration, and a mixed-methods approach to provide a more comprehensive picture of the effectiveness of productive question-based inquiry learning.

4. CONCLUSION

This study concludes that the implementation of structured inquiry learning based on productive questions significantly improves students' critical thinking skills and conceptual understanding compared to conventional learning. This is indicated by differences in posttest scores, an increase in N-gain in the moderate to high categories, and a relatively large effect size value, which confirms the strong influence of the treatment on student learning outcomes. These findings indicate that active student engagement through productive questions can encourage higher-order thinking processes and strengthen conceptual understanding in a meaningful way. Thus, structured inquiry learning based on productive questions can be used as an effective alternative learning strategy to support the achievement of learning objectives and the development of 21st-century skills, although further research is still needed to test the sustainability of its impact and its application in broader learning contexts.

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AUTHOR CONTRIBUTIONS

Conceptualization, A. and R.A.R.; Methodology, A.; Software, A.; Validation, A. and R.A.R.; Formal Analysis, A.; Investigation, A.; Resources, R.A.R.; Data Curation, A.; Writing – Original Draft Preparation, A.; Writing – Review & Editing, A. and R.A.R.; Visualization, A.; Supervision, R.A.R.; Project Administration, R.A.R.; Funding Acquisition, R.A.R.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

Not applicable.

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