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Enhancing Students Metacognitive Awareness and Scientific Reasoning through the Quantum Learning Model in High School

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Abstract: Students' limited ability to connect theoretical concepts with real-life phenomena, coupled with monotonous lecture-based teaching, has led to low engagement in learning. This study investigates the effect of the Quantum Learning model on students' metacognitive skills and scientific reasoning. Using a quasi-experimental design with a nonequivalent control group, the study involved 41 tenth-grade students at SMA 1 Labuapi, divided into an experimental group (n = 20) and a control group (n = 21), selected through saturated sampling. The Metacognitive Skills Scale (MSS), adapted from Mustafa and Nuray, and a scientific reasoning test based on the Classroom Test of Scientific Reasoning (CTSR) developed by Lawson, were used for data collection. Data were analyzed using paired sample t-tests at a significance level of $\alpha = 0.05$. Results showed significant improvement in both groups, with the experimental group experiencing greater gains in metacognitive skills (mean diff. = -20.050; SD = 5.624; p = 0.000) and scientific reasoning (mean diff. = -32.200; SD = 5.978; p = 0.000) compared to the control group (metacognitive: -11.905; SD = 5.558; scientific reasoning: -14.619; SD = 5.826; both p = 0.000). These findings indicate that the Quantum Learning model is effective in enhancing metacognitive awareness as well as scientific reasoning and is recommended for use in science education to improve student engagement and thinking skills.

Keywords: Biology; High School; Metacognition; Scientific Reasoning; Quantum Learning.

Introduction

Biology education in Indonesia faces significant challenges, particularly in connecting theoretical concepts with real-world phenomena. The 2022 PISA report highlighted this issue by ranking Indonesian students 74th out of 81 countries in science literacy. These findings suggest that Indonesian students still struggle with scientific reasoning, performing well below the OECD benchmark [1]. This problem is partly due to the dominance of traditional, concept-oriented teaching methods that often neglect crucial skills like metacognitive and scientific reasoning [2]. Consequently, there is an urgent need for more effective learning models that can simultaneously foster conceptual understanding, metacognitive awareness, and scientific reasoning skills.

Given biology's inherently complex and abstract content, metacognitive ability is essential for supporting meaningful learning. Metacognition refers to students' awareness and regulation of their own thinking processes, which helps them grasp and retain scientific concepts more effectively. However, over 80% of students face difficulties in applying metacognitive strategies, which limits their comprehension of biology content [3]. Enhancing metacognitive skills is crucial to help students become independent, efficient, and systematic problem-solvers [4]. These skills are particularly beneficial for complex topics like biotechnology, which require students to integrate theoretical knowledge with practical application. Enhancing metacognitive skills is crucial to help students become independent, efficient, and systematic problem-solvers [5].

The development of scientific reasoning significantly contributes to improving the effectiveness of science education. Scientific reasoning equips students to formulate hypotheses, design and carry out investigations, interpret data, and systematically manage experimental variables [6]. This skill is a key component of PISA assessments, in which Indonesian students have consistently underperformed in science and mathematics. Therefore, improving scientific reasoning within biology classes is critical for boosting academic achievement and preparing students for global scientific and technological challenges.

Unfortunately, conventional methods such as lectures and textbook-based assignments often fail to nurture metacognitive and scientific reasoning skills, leading to low student engagement. Furthermore, optimal learning requires a classroom environment that fosters joy and aligns with students' diverse learning styles, auditory, visual, and kinesthetic [7]. This highlights the need for innovative teaching models that stimulate both cognitive and emotional engagement.

One promising alternative to address these educational challenges is the implementation of the Quantum Learning model. Rooted in quantum physics, which explores the relationship between energy and light, Quantum Learning was developed by Bobbi DePorter and Mike Hernacki based on the educational and psychological approach introduced by Dr. Georgi Lozanov, a Bulgarian expert. This model transforms students' potential (energy) into success (light) through a comprehensive and structured learning process. It integrates brain-compatible learning principles and focuses on both academic skills and lifelong

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learning strategies [8]. One of the core components of Quantum Learning is the TANDUR framework: Grow, Experience, Name, Demonstrate, Repeat, and Celebrate, which allows students to explore their potential, understand concepts more deeply, and build confidence in expressing their thoughts [9]. Quantum learning also encourages students to build a positive emotional connection with the subject matter, which can enhance their engagement in the learning process [10].

In parallel, strengthening metacognitive awareness is vital. The concept of metacognition was first introduced by Flavell in 1976, after observing that many students failed to apply learning strategies due to a lack of awareness about their own learning processes. Flavell described metacognition as "thinking about thinking" [11]. According to Wilson and Clarke (2004), the metacognitive process includes three major components: awareness, regulation, and evaluation. These components enable students to become adaptive, self-regulated learners by involving declarative, procedural, and conditional knowledge along with planning, monitoring, and evaluating tasks [12]. As such, it is imperative for educators to teach and facilitate the development of metacognitive awareness within academic settings.

Scientific reasoning, as defined by Lawson (2004), is the process of generating causal conclusions about phenomena that cannot be directly observed, using mental rules, strategies, or tactics. This ability is crucial because it allows students to extrapolate underlying mechanisms from observable facts [13]. Scientific reasoning also involves six core aspects: conservation reasoning, proportional reasoning, control of variables, correlational reasoning, probabilistic reasoning, and hypothetical-deductive reasoning. These components collectively support students in applying their knowledge to solve various real-world problems [14].

In summary, integrating the Quantum Learning model with explicit instruction in metacognitive and scientific reasoning strategies offers significant potential to improve the quality of biology education in Indonesia. By aligning teaching practices with brain-compatible and student-centered approaches, this model can increase both engagement and learning outcomes, helping students develop the critical thinking and problem-solving skills essential for thriving in the 21st-century scientific landscape.

Research Methods

This study employed a quantitative approach using a quasi-experimental design, specifically the nonequivalent control group design, to investigate the effectiveness of the Quantum Learning model in enhancing students' metacognitive skills and scientific reasoning. The study population included all tenth-grade students at SMA Labuapi, totalling 41 students. Participants were divided into two groups: the experimental group (n = 20), which received instruction using the Quantum Learning model, and the control group (n = 21), which was taught using conventional methods. The sampling technique used was saturated sampling, involving all students in the selected classes [15]. The intervention was carried out over three learning sessions, consisting of two core instructional sessions and one practicum session conducted in the afternoon.

The design used in this study was the Nonequivalent Control Group Design. In this design, neither the experimental group nor the control group is selected randomly.

Table 1. Nonequivalent Control Group Design

Kelas	Pretest	Treatment	Posttest
K	O1 (e)	X	O2 (e)
E	O1 (k)	-	O2 (k)

Data were collected through two instruments: a 30-item questionnaire adapted from the Metacognitive Skills Scale (MSS) developed by Mustafa and Nuray [16], and a scientific reasoning essay test consisting of 10 items based on the Classroom Test of Scientific Reasoning developed by Lawson [17]. Both instruments underwent validity and reliability testing to ensure accurate and consistent measurement. The validation results confirmed that all items were valid, as presented in Table 2.

Table 2. Instrument Validation Result

Instrument	Number of Items	Validity Value	Category
Metacognitive Skills Scale	30	0.41-0.65	Valid
Scientific Reasoning Test	10	0.63 - 0.83	Valid

In addition to validation, students' learning outcomes were analyzed using the paired sample t-test at a significance level of $\alpha = 0.05$ to determine whether there were statistically significant differences in metacognitive skills and scientific reasoning before and after the intervention. The Normalized Gain (N-Gain) analysis was also employed to assess the magnitude of improvement in each group. The classification of N-Gain scores is shown in Table 3.

Table 3. N-Gain Score Categories

N-Gain Score	Category
>0.7	Hight
0.3 -0.7	Moderate
<0.3	Low

To interpret students' levels of metacognitive ability, a scoring rubric was used as outlined in Table 4. These score categories provided a framework for analyzing the impact of the Quantum Learning model on students' metacognitive awareness and scientific reasoning.

Table 4. Metacognitive Skills Score Categories

Score Range	Category
30-60	Low
61-90	Medium
91-120	Hight

Before conducting the hypothesis testing, prerequisite tests were administered, including tests for normality and homogeneity, to ensure the data met the assumptions required for parametric analysis. The main statistical analysis focused on determining whether the application of the Quantum Learning model resulted in significant improvements in students' metacognitive and scientific reasoning skills compared to conventional instruction.

Results and Discussion

Based on the results obtained from the pretest and posttest assessments, the learning outcomes of students in both the control and experimental classes showed significant differences. The metacognition pretest was conducted on February 5, 2025, for the control class and on February 6, 2025, for the experimental class. The posttest was administered on February 19, 2025, for the control class and on February 20, 2025, for the experimental class. The results of the metacognition questionnaire are presented in Figure 1.

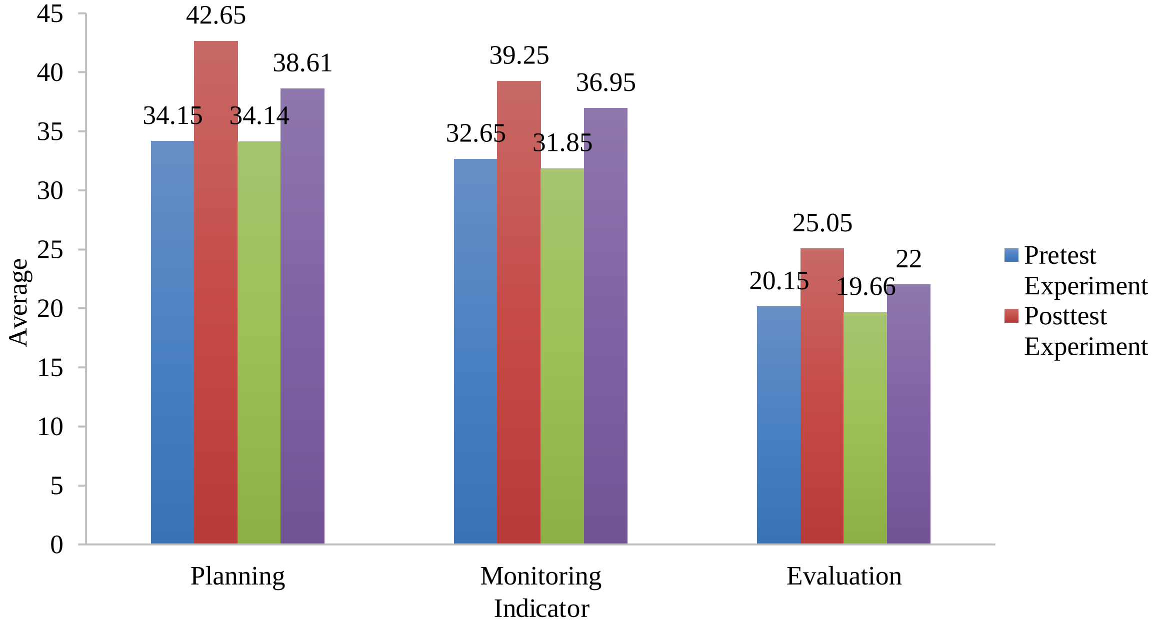

Figure 1. Metacognitive Data

The results revealed that students in the experimental group experienced a higher increase in all metacognitive aspects, planning, monitoring, and evaluation, after the implementation of the Quantum Learning model. Planning improved from 34.15 to 42.65, monitoring from 32.65 to 39.25, and evaluation from 20.15 to 25.05. In contrast, although the control group also showed progress, the gains were lower: planning from 34.14 to 38.61, monitoring from 31.85 to 36.95, and evaluation from 19.66 to 22. These findings indicate that the Quantum Learning model is more effective in enhancing students' metacognitive skills compared to conventional learning methods.

To determine the extent of improvement after the intervention, an N-gain analysis was conducted. Table 5.

Table 5. Metacognitive N-Gain Test Result

Group	Category		
	Low	Moderate	Hight
Experimental	0	17	3
Control	9	12	0

In the experimental group, 3 students achieved a high category, 17 were in the moderate category, and none were in the low category, with an average N-gain score of 59.91%. In contrast, the control group had no students in the high category, 12 in the moderate category, and 9 in the low category, with an average N-gain of 33.74%.

A normality test was conducted using the Shapiro-Wilk method to determine whether the data were normally distributed. The analysis results are presented in Table 6.

Table 6. Result of the Metacognitive Normality Test

Variable	N	Shapiro-Wilk	Description
Pretest (Metacognitive)	41	0.325	Normal
Posttest (Metacognitive)	41	0.396	Normal

The Asympt. Sig. (2-tailed) value for metacognition in the pretest was 0.325 and 0.396 in the posttest. Since both values are greater than the significance level of 0.05, it can be concluded that the data are normally distributed.

A homogeneity test was then conducted using the Levene method to determine whether the variances of the control and experimental classes were equal. Table 7.

Table 7. Result of the Metacognitive Homogeneity Test

Variable	N	Levene Test	Description
Pretest (Metacognitive)	41	0.296	Homogenous
Posttest (Metacognitive)	41	0.207	Homogenous

Shows that the significance value for metacognitive variables was 0.296 for the pretest and 0.207 for the posttest. As both values are greater than 0.05, the data can be considered homogeneous.

The scientific reasoning pretest was conducted on February 5, 2025, in the control class and on February 6, 2025, in the experimental class. The posttest was conducted on February 19, 2025, for the control class and February 20, 2025, for the experimental class. The results are presented in Figure 2.

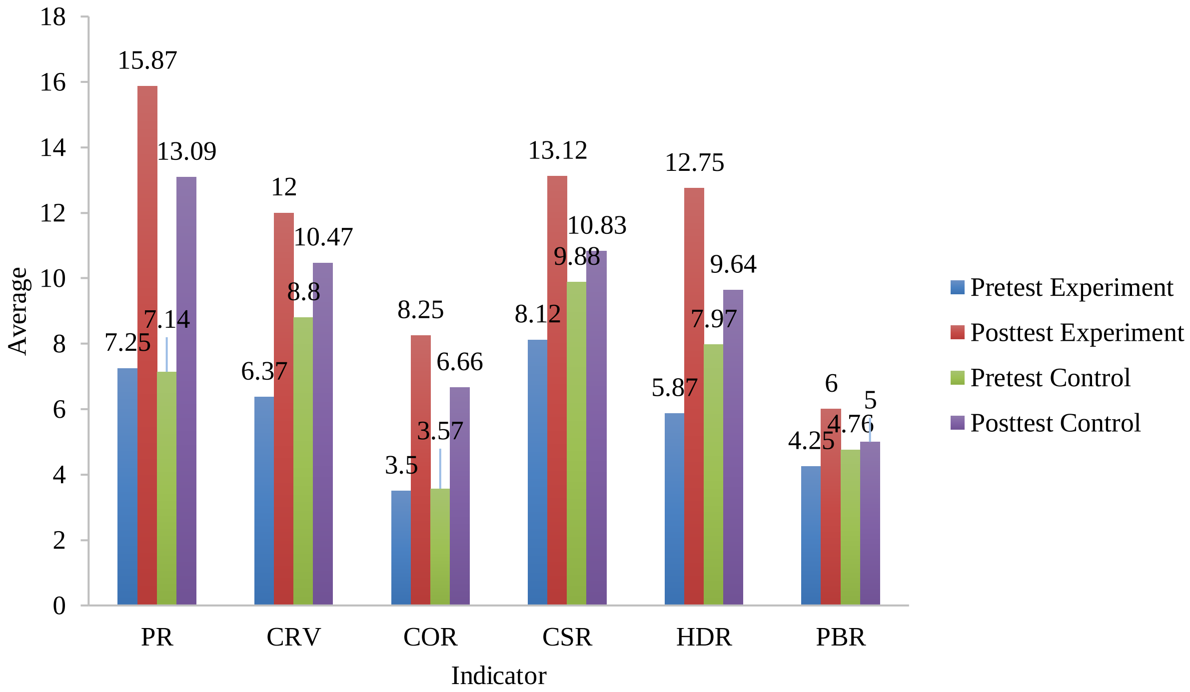

Figure 2. Scientific Reasoning Data

The results of the study indicate that all indicators of scientific reasoning in the experimental group showed a significant increase after the implementation of the Quantum Learning model, including Proportional Reasoning (PR) (from 7.25 to 15.87), Control of Variable (CRV) (from 6.37 to 12), Correlation Reasoning (COR) (from 3.5 to 8.25), Conservation of Form (CSR) (from 8.12 to 13.12), Hypothetico-Deductive Reasoning (HDR) (from 5.87 to 12.75), and Probabilistic Reasoning (PBR) (from 4.25 to 6). Although the control group also experienced increases across all indicators, such as Proportional Reasoning (PR) (from 7.14 to 13.09) and Hypothetico-Deductive Reasoning (HDR) (from 7.97 to 9.64), the improvement was less substantial. These findings suggest that the Quantum Learning model is more effective than conventional learning in enhancing students' scientific reasoning skills.

The N-gain analysis for scientific reasoning is presented in Table 8.

Table 8. Scientific Reasoning N-Gain Test Result

Group	Category		
	Low	Moderate	Hight
Experimental	0	20	0
Control	16	5	0

The average N-gain for the experimental class was 50.17%, with 20 students in the moderate category and none in the low category. In contrast, the control class had an average N-gain of 20.44%, with 13 students in the moderate category and 8 in the low category.

Normality testing for scientific reasoning was also conducted using the Shapiro-Wilk method. Table 9.

Table 9. Result of the Scientific Reasoning Normality Test

Variable	N	Shapiro-Wilk	Description
Pretest (Metacognitive)	41	0.105	Normal
Posttest (Metacognitive)	41	0.157	Normal

Shows that the Asymp. Sig. (2-tailed) values for pretest and posttest were 0.105 and 0.157, respectively. Since both are greater than 0.05, the data are normally distributed.

The homogeneity test results for scientific reasoning are shown in Table 10.

Table 10. Result of the Scientific Reasoning Homogeneity Test

Variable	N	Levene Test	Description
Pretest (Metacognitive)	41	0.163	Homogenous
Posttest (Metacognitive)	41	0.817	Homogenous

The significance value for the pretest was 0.163 and 0.817 for the posttest. As both values exceed 0.05, the data are considered homogeneous. The hypothesis testing was conducted using a paired sample t-test to compare the posttest means between the experimental and control classes. Table 11.

The results of the paired sample t-test indicate a significant difference between the posttest scores of the experimental and control groups in science learning outcomes, with a significance value of 0.001 (< 0.05) and a mean difference of 12.450. This suggests that the learning method applied in the experimental group was more effective. Regarding metacognitive ability, a significant difference was also found, with a significance value of 0.000 and a mean difference of 11.429. These results indicate that the applied learning method significantly improved students' metacognitive abilities compared to the control group.

Table 11. T-Test (Paired Sample T-Test) Result

Group	Std. Deviation	df	Sig. (2-tailed)	Description
Metacognitive (Experimental -Control)	9.223	20	0.000	H0 rejected
Scientific Reasoning (Experimental -Control)	14.299	20	0.001	H0 rejected

All significance values are less than 0.05, indicating statistically significant improvements in both metacognitive and scientific reasoning skills, particularly in the experimental class.

These findings indicate that students' metacognitive abilities and scientific reasoning improved more significantly when using the Quantum Learning model than with the Problem-Based Learning model. This study, conducted on the topic of Biotechnology for Grade X students at SMAN 1 Labuapi, showed a substantial increase in both aspects, with a significance value (Sig. 2-tailed) of 0.000, which is less than 0.05, thereby rejecting H_0 and accepting H_1. It can be concluded that the implementation of the Quantum Learning model significantly influences the improvement of students' metacognitive and scientific reasoning skills. These results are consistent with the study, which found that the Quantum Learning model can improve learning mastery, motivation, and students' higher-order thinking skills [18].

The greater improvement in the experimental class is attributed to differences in instructional approach. The control class employed Problem-Based Learning (PBL), which mainly relied on lectures and group problem-solving activities. In contrast, the experimental class implemented the Quantum Learning model, which consists of the stages Grow, Experience, Demonstrate, and Celebrate, each designed to promote active student engagement. At the Grow stage, learning began with contextual introductions and triggering questions aimed at stimulating curiosity and activating prior knowledge. According to previous studies, triggering questions can enhance thinking skills and help students articulate their thoughts clearly [19]. This stage supports students' metacognitive planning processes.

During the Experience stage, students were engaged in direct learning activities such as watching videos, participating in discussions, and taking quizzes. Experiential learning is a learning approach that actively engages students in the process of learning from experience, emphasizing a harmonious relationship between learning, working, and other learning activities in creating or discovering the desired knowledge [20]. These activities facilitated the development of metacognitive monitoring and evaluation skills while also training scientific reasoning through the analysis of multiple information sources. This stage also promotes the development of metacognitive strategies, which allow students to identify weaknesses in their understanding and improve learning strategies [21].

The Demonstrate stage involved exploratory tasks, including designing and conducting simple experiments. At this point, students planned and evaluated their experimental procedures, which cultivated both scientific investigation and critical thinking skills. Giving rewards can motivate students in the short term by providing external incentives to achieve specific goals [22]. Finally, in the Celebrate stage, positive reinforcement was provided through praise and rewards such as Quantum Star tokens. This form of appreciation increased students' motivation and encouraged them to continuously refine their learning strategies, further enhancing their metacognitive abilities and scientific reasoning.

Conclusion

Based on the results of data analysis, it can be concluded that the implementation of the Quantum Learning model has a significant effect on improving students' metacognitive abilities and scientific reasoning, with a significance value (Sig) of 0.000 < 0.05 on the topic of Biotechnology at SMAN 1 Labuapi in the 2024/2025 academic year. The Quantum Learning model has proven effective in enhancing students' cognitive engagement, understanding, and participation in biology learning. These results contribute to achieving competency-based learning outcomes by supporting the development of students' cognitive, metacognitive, and scientific reasoning skills. Future research may explore the implementation of the Quantum Learning model in other subjects or at different educational levels.

Author's Contribution

Saofiatul Aeni: contributed to the conceptualization and design of the study, data collection, data analysis, and manuscript writing. A. Wahab Jufri, Baiq Sri Handayani, and Agus Ramdani: supervised the overall research process, provided theoretical insights, and reviewed the final version of the manuscript. All authors have read and approved the final manuscript.

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