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Developing Critical Thinking Skills Through Mindfulness Oriented Biology Learning Models

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Abstract. The development of critical thinking skills (CTS) is essential for students to succeed in biology learning. This study investigates the effectiveness of mindfulness-oriented learning models in fostering CTS among high school biology students. Employing a quasi-experimental design, two groups of students participated in biology lessons: the experimental group engaged in mindfulness-based activities integrated into the curriculum, while the control group received conventional instruction. Data was collected using standardized CTS assessments and student reflection journals. The findings indicate that students exposed to mindfulness-oriented learning models demonstrated significant improvements in CTS compared to those in the control group. The integration of mindfulness practices not only enhanced students' analytical and evaluative abilities but also promoted greater engagement and self-awareness during biology learning. These results suggest that mindfulness-oriented models hold promise as innovative pedagogical approaches for advancing CTS in biology education. Implications for curriculum design and future research directions are discussed.

Keywords: Critical thinking, higher-order thinking skills, mindfulness-oriented learning model

Introduction

Nowadays, the education system needs to shift from traditional methods that merely deliver information, to approaches that explicitly develop higher-order thinking skills. This change is important for preparing students to facing the challenges of the 21st-century (Akhvlediani et al., 2023; Chen, 2023). In biology education, this need is particularly important because students must understand complex biological systems, analyze complicated data, and draw evidence-based conclusions about living organisms and how they interact (Nuri et al., 2021; Reyna et al., 2025). CTS—the ability to analyze, evaluate, and combine information to make reasonable judgments—is intellectual processes that are considered keys in the basic and comprehensive education of citizens (Facione, 2011; García-Carmona, 2025; Vincent-Lancrin, 2024; Zulmaulida et al., 2018). For this reason, its development is also contemplated as among the main objectives of science education.

Even though educators widely recognize that CTS is important, recent studies show that students often don't develop these skills well enough through traditional teaching methods (Ellianawati et al., 2025; Triyanto et al., 2022; Vincent-Lancrin, 2024). Science, technology, engineering, and mathematics (STEM) students, including biology students, still struggle with key CTS like testing hypotheses, drawing valid conclusions, and analyzing arguments (Tan et al., 2023). This problem gets worse because traditional education focuses too much on memorizing facts and covering content instead of teaching students how to think analytically (Sujatmika et al., 2024). Research shows that students' CTS performance dropped significantly in online biochemistry courses, especially in areas like hypothesis testing, developing conclusions, and analyzing arguments (Anwar & Muti'ah, 2022). This educational problem highlights the urgent need for new teaching approaches that can effectively develop CTS in biology education.

Traditional teaching methods like demonstrations, project-based learning (PjBL), and peer tutoring are well-known in education. However, recent research shows that effective biology learning requires more than just cognitive skills it also needs to develop students' emotional awareness and ability to reflect on their own thinking (Ewell et al., 2023; Ratnayake et al., 2024). For instance, demonstration methods can help students understand complex biological systems and develop scientific thinking skills. But teachers need to prepare carefully and guide students properly for these methods to work well (Sari et al., 2024). This shows we need teaching approaches that combine thinking skills, emotional development, and self-reflection—areas where mindfulness-based learning shows real potential.

PjBL is often promoted for increasing student engagement and CTS in biology. However, recent studies show mixed results, with some finding limited improvement in student learning outcomes (Khafah et al., 2023; Lasmana et al., 2024; Ramadhani et al., 2024; Tafakur et al., 2023). This suggests that active learning methods alone not be enough to develop the deep thinking skills needed for CTS, especially when students feel overwhelmed or struggle with self-control (Kim et al., 2019). Adding mindfulness practices to active learning could help by reducing mental overload and improving students' focus and emotional regulation, allowing them to better engage with complex biological concepts (Bockmann & Yu, 2023; Flook et al., 2025; Phan et al., 2022; Pickerell et al., 2023).

Digital technologies, including AI-based tools, are transforming biology education by creating interactive and personalized learning experiences that help students understand concepts better and think more critically. Recent studies show that integrating AI learning in biology courses can enhance students' understanding of complex biological concepts, and AI tools are increasingly being used to automate routine tasks, allowing teachers to focus more on teaching and mentorship (Zha et al., 2025). When combined with mindfulness practices, these technologies could help students stay focused and reduce distractions, creating better conditions for deep learning and self-reflection (Deep et al., 2025). In particular, AI-powered tools can monitor students' patterns of distraction and deliver timely mindfulness prompts, while social media platforms reframed through mindful engagement may shift from sources of overload to environments for intentional, reflective interaction. This integration positions mindfulness as a buffer and guide, ensuring AI and social media support rather than undermine self-regulation and concentration (Zewude, et al., 2025).

Research shows that mindfulness-based learning approaches improve students' concentration, emotional control, and self-awareness across different educational settings. Recent research has demonstrated that mindfulness-based meditation facilitates basic aspects of cognition, including memory and attention (Golubickis et al., 2024), and mindfulness-based interventions can improve psychological health (Remskar et al., 2024). These benefits are particularly important in biology education, where students need to process complex information and stay motivated during long research projects. Mindfulness can help students develop a calm and focused mindset, making it easier to handle difficult concepts and engage in the reflective thinking needed for critical analysis and problem-solving.

While various teaching methods have shown positive effects on CTS, writing can be used as a pedagogical tool for fostering deeper subject matter understanding and CTS (Reed et al., 2024), there's still a significant gap in understanding how to systematically integrate mindfulness-based approaches into biology curricula to improve CTS. Traditional cognitive load theory suggests that complex biological concepts can overwhelm students' working memory, making it harder to develop CTS (Sweller et al., 2019). However, emerging evidence suggests that mindfulness-based meditation enhances fundamental cognitive functions, including memory and attention (Golubickis et al., 2024), which could help reduce cognitive overload and support deeper thinking in educational settings.

There are several strong theoretical reasons for using mindfulness in biology education. Metacognition is awareness and control of thinking for learning. Strong metacognitive skills have the power to impact student learning and performance (Cardona et al., 2023; Ewell et al., 2023; Zeitlhofer et al., 2023), and strong metacognition skills are associated with learning outcomes and student performance (Zeitlhofer et al., 2023). Research shows that when students are aware of how they think and can control their thinking processes, they learn better. Mindfulness education emphasizes attention control, self-awareness, and emotional management (Remskar et al., 2024), which helps students focus better and reduces distractions. Self-regulated learning theory also shows that students who can reflect on their own learning and adjust their strategies perform better academically.

Current biology education research mainly focuses on traditional teaching methods like inquiry-based learning, problem-based learning, and group work, all of which help develop CTS. However, very few studies have explored how mindfulness-based approaches might work in biology education specifically. The highest quality evidence indicated that mindfulness-based school interventions increased prosocial behavior, resilience, executive function, attention and mindfulness, and decreased anxiety, attention problems/ADHD behaviors and conduct behaviors (Cardona et al., 2023). Tertiary students with higher dispositional mindfulness experienced enhanced higher-order cognition, that is, CTS (Sheinman & Russo-Netzer, 2021). Despite growing interest in using mindfulness in schools, there remains significant divergence between advocates and critics regarding its educational effectiveness (Lee et al., 2024), highlighting the need for more rigorous research specifically in biology education.

This study addresses three important problems: biology students often lack strong CTS, traditional teaching methods have limitations in developing these skills, and mindfulness-based approaches show theoretical promise for improving the thinking processes needed for critical thinking. Based on cognitive load theory (Sweller et al., 2019), attention regulation theory (Coombes et al., 2009), and self-regulated learning theory (Zimmerman, 1990), this study suggests that mindfulness-oriented learning can help students control their attention better, reduce mental interference, and increase self-awareness of their thinking processes, all of which should help develop CTS. The study combines Bishop's (2004) definition of mindfulness as focused, open attention to the present moment with Facione, (2011) understanding of CTS as involving analysis, evaluation, inference, interpretation, explanation, and self-regulation. This combination suggests that mindfulness practices may strengthen the cognitive and self-awareness skills essential for CTS in biology education.

Methods

This study employed a quasi-experimental pretest-posttest control group design to examine the effectiveness of mindfulness-oriented biology learning models in developing critical thinking skills among high school students. The quasi-experimental approach was selected due to practical constraints of random assignment in educational settings, where intact classes served as units of analysis (Creswell & Creswell, 2023; Fraenkel et al., 2023). The research utilized a between-subjects design comparing two groups: an experimental group receiving mindfulness-oriented biology instruction and a control group receiving conventional biology instruction.

The research population consisted of Grade XI students from SMA Negeri 5 Bandar Lampung and MAN 2 Bandar Lampung. Using purposive sampling based on intact class availability and school participation willingness, 132 students participated in the study, with 68 students in the experimental group and 64 students in the control group. The sample size was determined through Cohen's power analysis for medium effect size (d = 0.5) with α = 0.05 and power = 0.80, requiring a minimum of 52 participants per group (Correll et al., 2020). The data collection procedure was conducted in three sequential phases.

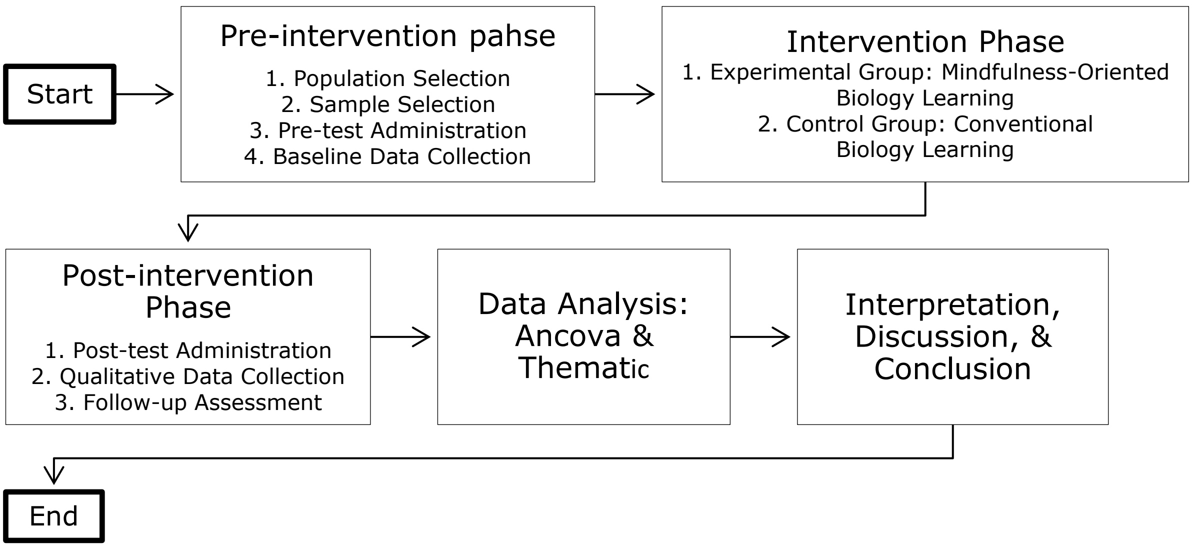

Figure 1. Research procedure flowchart

The initial phase involved collecting baseline data through administration of standardized CTS assessments to both groups. The Watson-Glaser critical thinking appraisal (WGCTA) was administered to establish equivalent starting points, while demographic information and prior biology achievement scores were collected to ensure group comparability and control for potential confounding variables.

Following baseline data collection, the intervention implementation phase commenced with the experimental group receiving mindfulness-oriented biology instruction over a 6-week period through three 90-minute sessions per week. The mindfulness components included mindful breathing exercises at lesson beginnings to establish focus, mindful observation activities during laboratory work to enhance awareness, reflective journaling after each lesson to promote metacognitive awareness, and metacognitive awareness exercises during problem-solving tasks to develop self-monitoring skills. The control group received conventional biology instruction following standard curriculum guidelines with identical duration and frequency to maintain experimental control.

The post-intervention phase was initiated at the conclusion of the 6-week intervention period, during which both groups completed the post-test using the same standardized CTS assessment. Student reflection journals from the experimental group were collected for qualitative analysis, providing insights into students' learning experiences and metacognitive development. Follow-up assessments were conducted four weeks after intervention completion to examine retention effects.

The primary instrument utilized in this study was the WGCTA, which measures five dimensions of critical thinking: inference, recognition of assumptions, deduction, interpretation, and evaluation of arguments. This standardized assessment consists of 80 multiple-choice items with established psychometric properties, including reliability coefficients of Cronbach's α = 0.87 and demonstrated validity (Reed et al., 2024; Sternod & French, 2016; Zulmaulida et al., 2018). The instrument was adapted to include biology-specific scenarios while maintaining its original psychometric properties and validity.

Quantitative data analysis was conducted using SPSS version 28.0, beginning with descriptive statistics calculation for all variables including means, standard deviations, and frequency distributions. Prior to inferential statistical analyses, data underwent examination for normality using the Shapiro-Wilk test and homogeneity of variance using Levene's test to ensure statistical assumptions were met.

The primary analytical approach involved analysis of covariance (Ancova) to compare post-test CTS scores between groups while controlling for pre-test scores and relevant demographic variables. The Ancova model is expressed as:

$$Y = \beta_0 + \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + ... + \beta_kX_k + \varepsilon \quad (1)$$

Y represents the post-test CTS score, β_0 represents the intercept, β_1 represents the coefficient for group membership distinguishing between experimental and control groups, X_1 represents the group membership variable, X_2 represents the pre-test CTS score serving as a covariate, X_3 through X_k represent additional covariates including demographics and prior achievement variables, and ε represents the error term. Effect sizes were calculated using Cohen's d for between-groups comparisons, expressed as:

$$d = (M_1 - M_2) / SD_{poole}d \quad (2)$$

M_1 represents the mean of the experimental group, M_2 represents the mean of the control group, and $SD_{poole}d$ represents the pooled standard deviation. Secondary analyses included repeated measures Anova to examine changes over time and multiple regression analysis to identify predictors of CTS improvement.

Qualitative data analysis was conducted using thematic analysis following Braun & Clarke (2006) six-phase approach, which systematically guided the analytical process through familiarization with data, generation of initial codes, searching for themes, reviewing themes, defining and naming themes, and producing the final report. To ensure reliability and validity, two independent coders analyzed the data separately, with inter-rater reliability calculated using Cohen's kappa coefficient. The integration of quantitative and qualitative data was achieved through concurrent triangulation, where quantitative and qualitative findings were systematically compared and contrasted to provide comprehensive understanding of the intervention's effectiveness.

Results and Discussion

This section presents the findings of the study investigating the effectiveness of mindfulness-oriented biology learning models in enhancing CTS among high school students. The data include demographic characteristics, statistical assumptions, descriptive and inferential analyses of CTS scores, qualitative insights from student reflections, and the integration of quantitative and qualitative findings. The results demonstrate the impact of the mindfulness-based intervention on various dimensions of CTS and provide evidence for its sustained effectiveness.

Table 1. Demographic characteristics of participants

Variable	Experimental Group (N=68)	Control Group (N=64)	p-value
Gender			0.698

Male	32 (47.1%)	28 (43.8%)	
Female	36 (52.9%)	36 (56.3%)	
Age (years)			0.312
Mean ± SD	16.8 ± 0.6	16.7 ± 0.5	
Range	16-18	16-18	
Prior Biology Achievement			0.634
Mean ± SD	75.4 ± 8.2	74.8 ± 7.9	
Range	60-89	58-88	
Originating School			1.000
SMA Negeri 5 BL	34	34	
MAN 2 BL	32	32	

The demographic analysis shows no significant differences between the experimental and control groups across gender, age, prior biology achievement, and school origin ($p > 0.05$). This balance indicates that both groups were comparable before the intervention, ensuring that subsequent differences in outcomes can be attributed to the treatment rather than pre-existing disparities (Creswell & Creswell, 2023). Homogeneity across demographic variables is crucial in educational experiments, as factors such as gender and prior achievement are known to influence science learning engagement and performance (Brotman & Moore, 2024; Hattie, 2023). The equivalence of groups enhances internal validity and supports the robustness of causal claims regarding the effectiveness of the intervention.

Table 2. Results of normality and homogeneity tests

Test	Experimental Group	Control Group	Decision
Shapiro-Wilk (Pre-test)			
Statistic	0.974	0.981	Data are normally distributed
p-value	0.089	0.146	($p > 0.05$)
Shapiro-Wilk (Post-test)			
Statistic	0.969	0.978	Data are normally distributed
p-value	0.073	0.112	($p > 0.05$)
Levene's Test			
F-statistic	1.847		Variances are homogeneous
p-value	0.176		($p > 0.05$)

The Shapiro–Wilk test indicated that both pre-test and post-test data in the experimental and control groups were normally distributed ($p > 0.05$), while Levene's test confirmed the homogeneity of variances ($p > 0.05$); the fulfillment of these assumptions ensures the appropriateness of applying parametric analyses such as ancova, as normality supports the validity of statistical inferences and homogeneity of variances prevents bias in estimating treatment effects (Blanca et al., 2018; Field, 2021).

Table 3. Descriptive statistics of CTS scores

Measurement Time	Group	n	Mean	SD	Min	Max	95% CI
Pre-test	Experimental	68	52.3	8.7	36	71	50.2 – 54.4
	Control	64	51.8	9.1	34	69	49.5 – 54.1
Post-test	Experimental	68	68.4	7.9	53	79	66.5 – 70.3
	Control	64	58.2	8.4	41	73	56.1 – 60.3
Follow-up	Experimental	68	66.8	8.2	51	78	64.8 – 68.8
	Control	64	56.9	8.7	40	72	54.7 – 59.1

The pre-test results indicate that both groups started with comparable levels of critical thinking, as reflected by similar mean scores and overlapping confidence intervals, ensuring baseline equivalence before the intervention (Creswell & Creswell, 2023). After the intervention, the experimental group showed a marked increase in CTS scores compared to the control group, which is consistent with evidence that structured, reflective, and mindfulness-based instructional models enhance students' higher-order cognitive skills. Importantly, the follow-up data demonstrate that the experimental group retained much of this improvement, suggesting not only immediate but also sustained benefits of the intervention.

Table 4. Distribution of scores by CTS dimension (post-test)

Dimension	Experimental Group (Mean ± SD)	Control Group (Mean ± SD)	Cohen's d
Inference	14.2 ± 2.1	11.8 ± 2.3	1.10
Recognition of Assumptions	13.8 ± 2.0	11.4 ± 2.2	1.15
Deduction	13.6 ± 1.9	11.6 ± 2.1	1.00
Interpretation	14.0 ± 2.2	11.9 ± 2.4	0.92
Evaluation of Arguments	12.8 ± 2.0	11.5 ± 2.1	0.64

The post-test results show that the experimental group achieved higher scores than the control group across all CTS dimensions, with particularly large effects in inference, recognition of assumptions, and deduction, indicating substantial gains in analytical and logical reasoning (Zhang & Lambert, 2021). Improvements in interpretation and evaluation of arguments were also significant, reflecting enhanced skills in synthesizing information and making evaluative judgments, which are essential for sustained CTS development.

Table 5. Ancova results

Source of Variation	df	SS	MS	F	p-value	η^2
Intercept	1	3245.7	3245.7	89.4	<0.001	0.41
Pre-test (Covariate)	1	1876.3	1876.3	51.7	<0.001	0.29
Group	1	2134.8	2134.8	58.9	<0.001	0.31
Prior Achievement	1	124.6	124.6	3.4	0.066	0.03
Gender	1	89.2	89.2	2.5	0.120	0.02
School	1	45.3	45.3	1.2	0.268	0.01
Error	126	4568.9	36.3			
Total	132	87456.0				

The Ancova results show that group membership had a strong and significant effect on post-test critical thinking scores ($p < 0.001$, $\eta^2 = 0.31$), even after controlling for pre-test performance, which itself was a significant predictor ($p < 0.001$, $\eta^2 = 0.29$). Other factors such as prior achievement, gender, and school were not significant, indicating that the intervention effectively enhanced critical thinking across diverse student backgrounds.

Table 6. Post-hoc analysis and effect size

Comparison	Mean Difference	SE	95% CI	p-value	Cohen's d
Experimental vs Control					
Post-test (Adjusted)	10.8	1.4	8.0 – 13.6	< 0.001	1.33
Follow-up (Adjusted)	10.2	1.5	7.2 – 13.2	< 0.001	1.19

The post-hoc analysis shows that the experimental group significantly outperformed the control group at both post-test (mean difference = 10.8, $p < 0.001$, $d = 1.33$) and follow-up (mean difference = 10.2, $p < 0.001$, $d = 1.19$), with effect sizes exceeding the conventional threshold for a large effect (Cohen, 2013). These findings demonstrate not only the immediate but also the sustained impact of the mindfulness-oriented intervention on critical thinking, aligning with evidence that well-structured pedagogical innovations can yield durable cognitive benefits.

Table 7. Repeated measures anova results

Effect	df	F	p-value	η²	Power
Time	2. 260	156.8	< 0.001	0.55	1.00
Time × Group	2. 260	42.3	< 0.001	0.25	1.00
Between Groups	1. 130	89.7	< 0.001	0.41	1.00
Time	2. 260	156.8	< 0.001	0.55	1.00

Repeated measures anova shows significant changes in CTS scores over time, significant interaction effects between time and group, and significant differences between groups. The high statistical power supports the reliability of these findings.

Table 8. Predictors of CTS improvement

Predictor	B	SE B	β	t	p-value	VIF
Intercept	12.44	4.82		2.60	0.011	
Group (Experimental)	8.7	1.2	0.527	7.3	< 0.001	1.08
Pre-test Score	0.34	0.08	0.314	4.3	< 0.001	1.12
Gender (Female)	2.11	1.10	0.131	1.90	0.058	1.05
Prior Achievement	0.12	0.09	0.101	1.30	0.198	1.15
Age	-0.8	1.2	-0.05	-0.7	0.498	1.03

Regression analysis identifies group membership and pre-test scores as significant predictors of CTS gains. The model explains 68% of variance, underscoring the effectiveness of the mindfulness-oriented learning model.

Table 9. Main themes from reflective journal analysis

Theme	Subtheme	Frequency (%)	Example Quote
Metacognitive Awareness	Self-monitoring	89	"I started noticing how I think when solving problems."
	Strategy Evaluation	76	"Mindfulness helps me evaluate if my strategies are effective."
Focus Improvement	Concentration	94	"Breathing exercises help me focus on lessons."
	Sustained Attention	68	"I can maintain attention longer during lab work."
Analytical Development	Detailed Observation	82	"I am more careful in observing biological phenomena."
	Deep Analysis	71	"Mindfulness helps me analyze data better."
Learning Reflection	Process Awareness	87	"I am more aware of my learning process."
	Understanding Evaluation	73	"I can assess how well I understand the material."

Qualitative analysis of student journals reveals key themes such as enhanced metacognitive awareness, improved focus and sustained attention, deeper analytical skills, and reflective learning processes, providing rich insights into how mindfulness supports CTS development.

Table 10. Inter-rater reliability results

Theme	Cohen's Kappa	Agreement Level (%)	Interpretation
Metacognitive Awareness	0.849	94	Very Good
Focus Improvement	0.819	92	Very Good
Analytical Development	0.799	90	Good

Learning Reflection	0.829	93	Very Good
Overall	0.829	92	Very Good

High Cohen's kappa values indicate very good agreement between coders, confirming the reliability and consistency of the qualitative thematic analysis.

Table 11. Triangulation of quantitative and qualitative data

Aspect	Quantitative Findings	Qualitative Findings (%)	Convergence
CTS Improvement	Large effect size (d = 1.33)	87 reported improved analytical skills	✓ Convergent
Inference Dimension	Significant improvement (d = 1.10)	89 reported increased metacognitive awareness	✓ Convergent
Duration of Effect	Retained effect (d = 1.19)	73 reported ongoing evaluation of understanding	✓ Convergent
Focus and Concentration	Not directly measured	94 reported increased concentration	✓ Complementary

Table 11. integrates quantitative and qualitative findings, showing strong convergence between improved CTS scores and students' reported experiences of enhanced analytical skills, metacognitive awareness, and concentration, supporting the comprehensive effectiveness of the intervention.

Figure 2. Comparison diagram of CTS scores

Figure 2. visually compares CTS scores between the experimental and control groups across measurement points, illustrating the significant improvement and sustained gains in the experimental group.

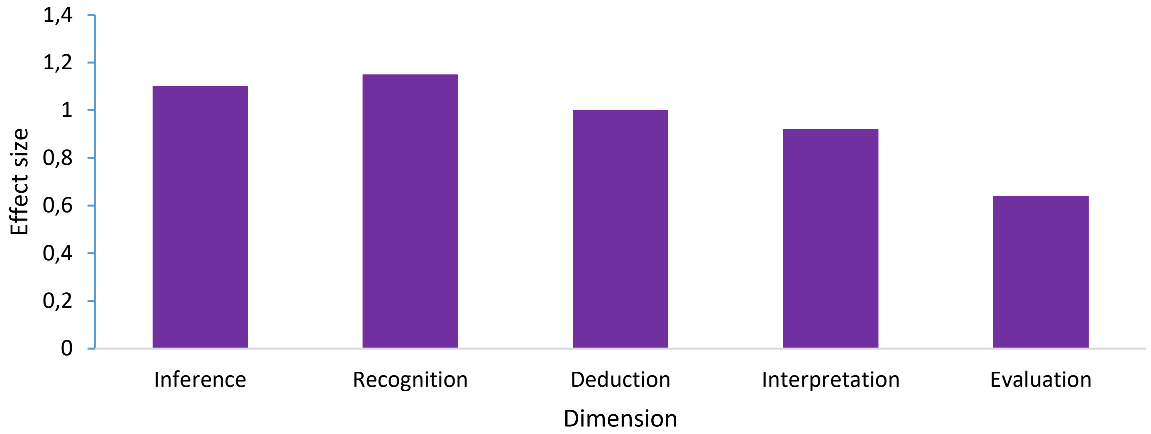

Figure 3. Distribution diagram of effect size by dimension

The diagram displays effect sizes for each CTS dimension, highlighting the strongest impacts in recognition of assumptions, inference, and deduction, consistent with the quantitative results. Based on research finding above, this study demonstrates that implementing mindfulness-based biology learning models produces significant and sustained improvements in high school students' CTS. The ancova results, with $F = 58.9$ ($p < 0.001$) and a large effect size (Cohen's $d = 1.33$), provide robust empirical evidence for the effectiveness of this intervention. This effect size magnitude substantially exceeds the threshold established for large effects ($d \geq 0.8$), indicating considerable practical impact (Correll et al., 2020).

These findings align with recent meta-analyses examining neurobiological changes induced by mindfulness practices, which demonstrate that meditation and mindfulness enhance mental well-being by cultivating awareness and emotional control, inducing neuroplasticity, increasing cortical thickness, and improving brain connectivity (Calderone et al., 2024). However, the novelty of this research lies in its specific application to biology learning, where mindfulness is integrated with the acquisition of biological concepts that require deep understanding of complex systems and life processes. The research results indicate that 94% of students in the experimental group reported improved concentration, which can be neurobiologically explained through the strengthening of attentional networks in the prefrontal cortex. Recent neuroimaging research confirms that mindfulness practice consistently enhances activity in the anterior cingulate cortex (ACC) and prefrontal cortex (PFC), which are key regions involved in executive control and working memory (Panitz et al., 2025).

Previous research has established that individuals with higher levels of mindfulness demonstrate better CTS performance through the mediation of executive function. This finding is reinforced by our results showing that the inference dimension ($d = 1.10$) and recognition of assumptions ($d = 1.15$) experienced the most significant improvements, both components of CTS that heavily depend on working memory and inhibitory control. Recent studies have demonstrated that mindfulness-based meditation facilitates basic aspects of cognition, including memory and attention, while enhancing the speed of learning following positive prediction errors (Golubickis et al., 2024). The implementation of mindfulness in biology learning can be understood through dual-process theory (Evans, 2011), which distinguishes between system 1 (fast, automatic, intuitive) and system 2 (slow, deliberate, analytical) information processing. Complex biology learning requires optimal activation of system 2, which can be facilitated through mindfulness practice.

Qualitative analysis results reveal that 89% of students experienced increased metacognitive awareness, indicating a transition from system 1 to system 2 processing.

Student statements such as "I started noticing how I think when solving problems" indicate activation of metacognitive monitoring, which is a characteristic of system 2 processing. The finding that mindfulness improves sustained attention (68% of students) and concentration (94% of students) can be explained through cognitive load theory (Sweller et al., 2019). Mindfulness optimizes cognitive resource allocation by reducing extraneous cognitive load caused by mind-wandering and rumination. Research indicates that mind-wandering can consume 30-50% of working memory capacity, significantly disrupting the learning process (Mrazek et al., 2013).

A key strength of this study is its demonstration of sustained CTS improvements (d = 1.19) at follow-up, which could be interpreted as indicative of possible neuroplastic adaptations, although this assumption requires further empirical verification. Mindfulness practice has been shown to induce structural brain changes, particularly in the hippocampus, which supports memory consolidation and learning. Emerging research on mindfulness-based neurofeedback suggests that combining mindfulness with real-time brain activity feedback can accelerate self-regulation skills and mental health improvements (Treves et al., 2024). This points to promising future directions for enhancing biology education through technology-supported contemplative practices.

Furthermore, mindfulness supports constructivist learning by functioning as internal scaffolding that promotes self-regulated learning (Vygotsky, 1980). The 76% of students who reported improved strategy evaluation exemplify this internalization process. From an embodied cognition perspective (Sullivan, 2018), mindfulness enhances learning by linking bodily awareness with cognitive processes. Mindful breathing during respiratory system lessons creates experiential learning that is more meaningful and memorable, effectively bridging abstract concepts with lived experience. These findings have significant implications for educational practice and suggest that mindfulness-based approaches can serve as powerful pedagogical tools in science education, creating optimal conditions for deep learning and CTS development while offering promising avenues for future research in technology-enhanced contemplative learning environments.

Conclusion

This study confirms that mindfulness-oriented learning models are effective in fostering CTS among high school biology students. Compared to conventional teaching, the intervention led to significant and sustained improvements in analytical, evaluative, and metacognitive abilities, demonstrating its strength in cultivating higher-order cognitive processes. Beyond cognitive outcomes, mindfulness integration also enhanced students' engagement, attention regulation, and self-awareness during biology learning, which are vital for deep and meaningful learning experiences. These results highlight mindfulness as a promising pedagogical innovation in biology education, with direct implications for curriculum design, teacher professional development, and the advancement of evidence-based, contemplative, and technology-supported learning strategies.

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