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Preparing Future Science Teachers: An Analysis of Scientific Literacy and Critical Thinking Skills of Biology Education Students

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Abstract

This study aims to analyze the profiles of scientific literacy and critical thinking skills (CTS) of prospective teachers in the Biology Education Program at Universitas Pendidikan Mandalika, and to identify the gap between current instructional practices and the conditions needed to more effectively support these competencies. A concurrent triangulation mixed-methods design was employed, integrating a scientific literacy test, a CTS test based on the Ennis framework, classroom observations, document analysis of syllabi and lesson plans, perception questionnaires, and semi-structured interviews. Participants comprised 64 undergraduate students from the third, fifth, and seventh semesters, selected through purposive sampling. The results indicate that students' scientific literacy was at a moderate level ($M = 67.03$; $SD = 7.97$), as was their critical thinking ($M = 65.23$), with the higher-order indicators of evaluation and inference identified as the weakest dimensions. One-way ANOVA revealed statistically significant differences across semester cohorts for both scientific literacy ($F = 4.273$; $p = 0.018$; $\eta^2 = 0.12$) and CTS ($F = 5.012$; $p = 0.010$; $\eta^2 = 0.14$), with post-hoc analysis localizing these differences specifically between the third and seventh semester cohorts. Pearson correlation analysis showed a moderate-to-strong positive relationship between scientific literacy and CTS ($r = 0.612$; 95% CI [0.45, 0.74]; $p < 0.01$). Qualitative findings reveal that learning remains predominantly lecturer-centered, with limited integration of inquiry-based activities and socio-scientific issues and minimal evidence-based argumentation. Triangulation indicates that instructional design factors, rather than students' inherent capacity alone, appear to be a primary contributor to the observed competency gap. These findings underscore the need to strengthen instructional design—particularly through the integration of inquiry-based learning, socio-scientific issue (SSI) frameworks, and evidence-based argumentation—to develop 21st-century competencies among prospective science teachers.

Keywords: Scientific literacy; Critical thinking skills; Prospective biology teachers; Needs analysis; Mixed-methods

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INTRODUCTION

Twenty-first-century education positions scientific literacy and critical thinking skills (CTS) as two fundamental competencies in preparing learners to navigate an increasingly complex world shaped by rapid scientific and technological advancement. Scientific literacy encompasses the capacity to understand scientific concepts, interpret data, evaluate evidence, and make reasoned decisions within real-world socio-scientific contexts (Anggraeni et al., 2022; García-Hernández et al., 2022). Critical thinking, in turn, refers to the ability to analyze arguments, assess the validity of evidence, and construct logical conclusions grounded in systematic reasoning (Ennis, 2016). The 4Cs framework—communication, collaboration, critical thinking, and creativity—further underscores the centrality of these competencies in equipping learners for the digital era and a knowledge-based society (Dewi et al., 2023; Prayogi et al., 2024). Empirical studies consistently demonstrate that inquiry-based, problem-based, and design-based learning approaches effectively strengthen both scientific literacy and CTS across educational levels, and that authentic assessment instruments are essential to capture the full range of these competencies (Anwar et al., 2023; Erkacmaz et al., 2023; Weidman & Salisbury, 2020).

Prospective biology teachers occupy a particularly strategic position in this educational landscape. As future science educators, they are expected not only to master biological content but also to model and cultivate scientific literacy and critical thinking among their own students. However, studies consistently show that scientific literacy and CTS levels among prospective biology teachers in Indonesia remain within the moderate-to-low range, with variation across institutions attributable to differences in curriculum design and instructional approaches (Firdaus et al., 2023; Rasis et al., 2023; Suwono et al., 2017). Additionally, students' scientific epistemology, digital literacy, and information literacy have been shown to influence their capacity to evaluate scientific claims and construct evidence-based arguments (Laelasari & Maisyanah, 2022; Prachagool et al., 2022). These interrelated factors suggest that the development of scientific literacy and CTS cannot be addressed in isolation; rather, they require integrated and contextually responsive instructional approaches.

A major challenge in developing these competencies within Biology Education programs in Indonesia lies in the persistent dominance of teacher-centered instruction and the limited integration of scientific inquiry and socio-scientific issues (SSI) into everyday learning practices. Curricula that emphasize factual knowledge acquisition and laboratory procedures often fail to provide meaningful opportunities for students to interpret data, evaluate scientific evidence, or engage in evidence-based argumentation (Heim et al., 2023; Woodham et al., 2016). Compounding this, alignment between learning objectives, instructional strategies, and assessment tools remains weak in many programs, undermining the conditions necessary for higher-order thinking to develop (Joachim et al., 2020; Widiatmo et al., 2019). Limited access to digital learning resources and open educational resources (OER) further constrains students' development of information literacy, a competency increasingly critical in an era characterized by misinformation (Ahmed et al., 2024; Lawton et al., 2018; Ryder et al., 2020). These structural and pedagogical constraints create a substantial gap between the 21st-century competency outcomes expected of prospective science teachers and the learning experiences actually provided within the program.

To situate this study within the existing literature, Table 1 provides a comparative overview of recent studies on scientific literacy and CTS among prospective biology teachers in Indonesia. This comparison highlights differences in study context, design, measurement instruments, and findings, underscoring the need for a study that simultaneously profiles both competencies within a single regional institutional context using a mixed-methods approach.

Table 1. Comparison of Prior Studies on Scientific Literacy and CTS among Prospective Biology Teachers in Indonesia

Author(s)	Institution/Region	Design	Variables Measured	Key Findings
Firdaus et al. (2023)	NTB, Indonesia	Quantitative, cross-sectional	Scientific literacy only	Moderate SL; limited inquiry integration
Rasis et al. (2023)	Yogyakarta, Indonesia	Quasi-experimental	Environmental literacy, CTS	Inquiry kits improved env. literacy; CTS not primary focus
Suwono et al. (2017)	Malang, Indonesia	Descriptive, quantitative	Scientific literacy only	Third-year students:

Author(s)	Institution/Region	Design	Variables Measured	Key Findings
				moderate-low SL profile
Prayogi et al. (2024)	NTB, Indonesia	Quasi-experimental	CTS only	Inquiry > traditional for CTS; no SL measure
Present study	Mataram, NTB, Indonesia	Concurrent triangulation mixed-methods	SL + CTS + instructional context	Both competencies moderate; instructional factors analyzed

Note. SL = Scientific Literacy; CTS = Critical Thinking Skills; NTB = Nusa Tenggara Barat.

Addressing this gap, the literature recommends a strategic shift toward integrative and contextual instructional designs. Models incorporating problem-based learning (PBL), inquiry-based learning, higher-order thinking skills (HOTS) orientation, and Science–Environment–Technology–Society (SETS) or SSI frameworks have been empirically shown to simultaneously strengthen scientific literacy and CTS by requiring students to engage with real-world scientific phenomena, evaluate multiple sources of evidence, and construct reasoned arguments (Cantona et al., 2023; Firdaus et al., 2023; Putri & Rusmini, 2021; Siew & Mapeala, 2016). The integration of educational technologies—including augmented reality (AR), digital learning platforms, and OER—further supports the development of these competencies by expanding access to credible scientific information and enabling the visualization of complex biological concepts (Ahmed et al., 2024; Demircioğlu et al., 2022). However, realizing these improvements requires a foundational step: empirically mapping the current profiles of scientific literacy and CTS among prospective teachers to identify precise instructional needs, rather than implementing interventions without a contextually grounded basis.

Theoretically, this study is anchored in the view that scientific literacy and critical thinking are mutually constitutive competencies: scientific literacy provides the knowledge substrate necessary for critical evaluation of scientific evidence, while critical thinking provides the cognitive processes through which scientific understanding is deepened and applied (Ennis, 2016; García-Hernández et al., 2022). This reciprocal relationship is further mediated by instructional design variables—specifically, the presence or absence of inquiry-based activities, socio-scientific issue integration, and evidence-based argumentation—as well as by structural enablers such as access to digital scientific resources (Ahmed et al., 2024). Ideal conditions for competency development are operationalized in this study as instructional environments in which: (a) learning objectives explicitly target both SL and CTS across multiple courses; (b) instructional strategies include inquiry, SSI, argumentation, and contextual problem-solving; (c) assessment instruments require evidence-based reasoning and higher-order responses; and (d) students have adequate access to peer-reviewed digital literature and OER. The degree of alignment between observed instructional conditions and these benchmarks constitutes the "gap" this study seeks to characterize.

Despite the growing body of research on scientific literacy and CTS in biology education, studies simultaneously profiling both competencies within a single regional institutional context—and linking quantitative profiles to qualitative analyses of instructional practice—remain scarce, particularly in Eastern Indonesian higher education settings. Existing studies tend to either measure one competency in isolation or report intervention outcomes without adequately characterizing baseline conditions and local contextual factors. To address this gap, the present study aims to: (1) identify the profiles of scientific literacy and CTS among prospective teachers in the Biology Education Program at Universitas Pendidikan Mandalika; (2) analyze the gap between current instructional practices and ideal learning conditions that support the development of these competencies; (3) explore supporting and inhibiting factors in implementing literacy- and CTS-oriented instructional strategies; and (4) formulate recommendations for instructional designs aligned with students' learning needs and 21st-century competency demands. Consistent with objectives (1) and (2), the study triangulates quantitative data (SL and CTS test scores) with qualitative data derived from classroom observations, document analysis of syllabi and semester lesson plans (RPS), semi-structured interviews, and perception questionnaires—each instrument directly aligned with a specific research objective. The novelty of this study lies in its integration of quantitative profiling with qualitative needs analysis within a specific regional context, providing an evidence base for adaptive, locally contextualized instructional development in biology teacher education.

METHOD

Research Design

This study employed a concurrent triangulation mixed-methods design (Creswell & Plano Clark, 2018), integrating quantitative and qualitative data collected simultaneously to provide a comprehensive understanding of prospective biology teachers' scientific literacy and critical thinking skills (CTS). In this design, quantitative and qualitative strands are given approximately equal weight; data are collected in parallel and merged at the interpretation stage to corroborate, expand, or explain findings. The quantitative strand focused on measuring and comparing students' competency profiles across semester cohorts, while the qualitative strand explored instructional practices and factors influencing competency development. Data were collected across three sequential phases: (1) standardized assessment of scientific literacy and CTS; (2) exploration of current instructional practices through classroom observations and document analysis; and (3) in-depth examination of supporting and inhibiting factors through semi-structured interviews and perception questionnaires. The integration of both strands enabled triangulation of findings, enhancing the validity and contextual depth of the conclusions drawn.

Research Participants and Setting

This study was conducted within the Biology Education Program at Universitas Pendidikan Mandalika. The total enrolled population in the Biology Education Program at the time of data collection comprised approximately 186 active students across all academic semesters. Participants were selected using purposive sampling to ensure representation across academic stages corresponding to the early, middle, and final phases of the undergraduate teacher education program. Eligibility criteria required participants to be active Biology Education students who had completed at least two core pedagogical and biological content courses, such as Biology Teaching Strategies and Learning Evaluation. A total of 64 students participated, comprising 20 students from the third semester, 22 from the fifth semester, and 22 from the seventh semester. The sample was predominantly female ($n = 49$, 76.6%), with a mean age of 20.8 years ($SD = 1.3$). For the qualitative strand, a purposive sub-sample of 12 students (4 per semester) participated in semi-structured individual interviews, selected to represent variation in test performance (high, medium, and low scorers). Classroom observations were conducted across 6 class sessions (2 per semester group), each lasting approximately 90 minutes, covering a range of course types (content, pedagogy, and laboratory). A total of 5 RPS documents (semester lesson plans) from courses directly associated with scientific literacy and CTS development were systematically analyzed. This three-cohort structure enabled cross-sectional analysis of competency variation across academic stages of the undergraduate program.

Research Instruments

Scientific Literacy Instrument

Scientific literacy was assessed using a test developed based on four indicators: (1) the ability to understand scientific concepts within real-life contexts; (2) the ability to interpret and analyze scientific data or information presented in graphs, tables, or scientific narratives; (3) the ability to critically evaluate scientific evidence and claims; and (4) the ability to apply scientific concepts in decision-making related to socio-scientific issues (SSI). These indicators were developed in reference to the frameworks proposed by Afnan et al. (2023) dan Anggraena et al. (2022). The instrument consisted of 20 items in total: 12 complex multiple-choice items (5 options each) and 8 open-ended items requiring contextualized written responses. Items addressed contemporary scientific issues such as environmental problems, food technology, and public health, presented through graphs, tables, and brief scientific texts. Each multiple-choice item was scored dichotomously (0–1), while open-ended items were scored on a 0–4 analytic rubric encompassing accuracy of scientific concept application, quality of reasoning, and relevance to the SSI context. Total raw scores were converted to a 0–100 scale. Based on pilot data and the scoring distribution, competency categories were defined as: High (≥75), Moderate (50–74), and Low (<50). The instrument was administered within a 60-minute time allocation.

Critical Thinking Skills Instrument

Critical thinking skills were assessed using a test constructed based on the California Critical Thinking Skills Test (CCTST) framework and Ennis's (2016) indicators, encompassing five aspects: (1) Clarification; (2) Analysis; (3) Inference; (4) Evaluation; and (5) Explanation. The test comprised 18 items in total: 10 reasoning-based multiple-choice items and 8 short-answer items requiring participants to provide evidence-based justifications. Each indicator was represented by 3–4 items. Multiple-choice items were scored dichotomously (0–1); short-answer items were scored on a 0–4 rubric assessing logical soundness, evidence use, and argument clarity. Total scores were converted to a 0–100 scale using the same categorization cutoffs as the SL test (High ≥75, Moderate 50–74, Low <50). The instrument was likewise administered within 60 minutes.

Supporting Qualitative Instruments

To support qualitative data collection and triangulation, three additional instruments were employed: (1) structured classroom observation sheets, used to document instructional strategies, student engagement, and integration of inquiry-based activities; (2) semi-structured interview guides, designed to elicit in-depth insights into students' learning experiences and perceptions of instructional quality; and (3) Likert-scale learning perception questionnaires, used to map students' self-reported experiences in developing scientific literacy and CTS. Course-related documents—including syllabi and semester lesson plans (RPS)—were also analyzed as secondary data to assess alignment between instructional practices and curricular objectives.

Validity and Reliability

All instruments underwent a two-stage validation process. First, content validity was established through expert review by three specialists in science education and instructional measurement (two with expertise in biology education assessment and one in educational psychology), who assessed the relevance, clarity, and representativeness of each item against the targeted indicators. Second, a pilot study was conducted with 28 Biology Education students (from a semester not included in the main study) outside the main research sample to evaluate item difficulty, discrimination indices, and time appropriateness. Item difficulty indices (p) for the SL test ranged from 0.32 to 0.68 ($M = 0.51$, classified as moderate), and discrimination indices (D) ranged from 0.31 to 0.65 ($M = 0.47$, classified as good-to-excellent). For the CTS test, difficulty indices ranged from 0.35 to 0.67 and discrimination indices from 0.30 to 0.62, indicating acceptable item quality. Items with $p < 0.20$ or $D < 0.20$ were revised or replaced prior to main data collection. The scientific literacy test yielded a Cronbach's alpha reliability coefficient of $\alpha = 0.86$, and the CTS test yielded $\alpha = 0.82$, both exceeding the minimum acceptable threshold of .70 for research instruments (Fraenkel et al., 2012). The analytic rubric for open-ended items was validated through inter-rater reliability assessment, yielding a Cohen's Kappa of $\kappa = 0.84$, indicating substantial to near-perfect agreement. The qualitative instruments were reviewed for face validity by a qualitative research expert to ensure clarity and appropriateness of question framing.

Data Collection Procedures

All instruments were prepared in both printed and digital formats to facilitate flexible administration in regular classroom settings. The scientific literacy and CTS tests were administered simultaneously under controlled classroom conditions, each with a 60-minute completion window. An orientation session was conducted prior to data collection to explain the study's objectives, procedures, and ethical considerations, ensuring all participants had a clear understanding of the tasks before beginning. Classroom observations were conducted across multiple sessions to document naturally occurring instructional practices, and interviews were conducted individually in a semi-structured format following test administration to minimize interference with regular coursework. Questionnaires were distributed digitally and collected within the same week as the test to ensure temporal consistency in data.

Data Analysis

Quantitative data from the scientific literacy and CTS tests were analyzed using both descriptive and inferential statistics in IBM SPSS Statistics version 26. Descriptive statistics—including means, standard deviations, and minimum and maximum scores—were calculated for each variable and used to categorize students' competency levels into high, moderate, and low categories. Prior to inferential analysis, the assumptions of normality and homogeneity of variance were verified. Normality was examined using the Shapiro–Wilk test for each semester group ($n < 50$): all groups yielded non-significant results (SL: $W = 0.961–0.973$, $p > 0.05$; CTS: $W = 0.958–0.971$, $p > 0.05$), confirming approximate normality. Homogeneity of variance was tested using Levene's test: results were non-significant for both SL ($F = 0.87$, $p = 0.42$) and CTS ($F = 1.14$, $p = 0.33$), confirming equal variances across semester groups. These results justified the use of one-way ANOVA. To examine differences in scores across semester groups (third, fifth, and seventh semesters), one-way analysis of variance (ANOVA) was conducted at a significance level of $\alpha = 0.05$. Effect size was estimated using eta-squared (η^2). Where significant differences were detected, post-hoc Tukey HSD tests were performed to identify specific group pairs exhibiting statistically significant differences. The relationship between scientific literacy and CTS was examined using Pearson's correlation coefficient (r), with a 95% confidence interval reported. Strength benchmarks followed Cohen (1988): $r = 0.10–0.29$ (small), 0.30–0.49 (moderate), ≥0.50 (large).

Qualitative data from classroom observations, interviews, and questionnaires were analyzed using thematic analysis in NVivo version 12, following a systematic process of open coding, category formation, and theme development (Braun & Clarke, 2006). Two independent coders conducted initial coding; disagreements were resolved through discussion until consensus was reached. Inter-coder agreement was calculated using Cohen's Kappa ($\kappa = 0.81$), indicating strong agreement and supporting the trustworthiness of the thematic analysis. Qualitative themes were subsequently integrated with quantitative findings through a convergent triangulation strategy to produce interpretive conclusions that draw on the full range of evidence collected.

Ethical Considerations

This study was conducted in full compliance with relevant national regulations, institutional policies, and the ethical principles of the Declaration of Helsinki. Ethical approval was obtained from the Institutional Review Board of Universitas Pendidikan Mandalika (Approval No.: 045/LPPM-UNDIKMA/XI/2023; date: 12 November 2023) prior to data collection. All participants were provided with a written explanation of the study's objectives, procedures, and their rights, including the right to withdraw at any time without consequence and the assurance of data confidentiality. Written informed consent was obtained from all participants before the study commenced. Participant anonymity was preserved throughout data collection, analysis, and reporting.

RESULTS AND DISCUSSION

Students' Scientific Literacy Profile

The assessment of scientific literacy among 64 Biology Education students indicated that competency levels were predominantly moderate across all semester cohorts. Mean scores ranged from 62.35 in the third-semester cohort to 71.23 in the seventh-semester cohort (out of a maximum of 100), with higher-semester cohorts demonstrating progressively higher mean scores. Despite this increase, no semester group reached the high category overall, suggesting that scientific literacy varies across academic cohorts but remains below optimal levels at every stage examined.

Table 2. Scientific Literacy Scores of Biology Education Students by Semester Cohort

Semester	n	Mean	SD	Min	Max	Category
III	20	62.35	8.42	48	75	Moderate
V	22	67.18	7.56	52	80	Moderate
VII	22	71.23	6.94	58	84	Moderate–High
Total	64	67.03	7.97	48	84	Moderate

The steady rise in mean scores across cohorts is consistent with greater accumulated learning experience among higher-semester students, though the cross-sectional design of this study precludes causal inference about within-student growth. The consistent classification within the moderate range indicates that current instructional conditions have not yet enabled students to reach the higher levels of scientific reasoning and contextual application expected of prospective science teachers.

Critical Thinking Skills (CTS) Profile

The assessment of critical thinking skills revealed a pattern consistent with the scientific literacy findings, with overall CTS levels falling within the moderate category and higher-semester cohorts demonstrating higher mean scores. Analysis across the five Ennis indicators showed that clarification and analysis were comparatively more developed, whereas inference and evaluation remained the weakest dimensions.

Table 3. Critical Thinking Skills Scores by Semester Cohort and Indicator

CTS Indicator	Sem III	Sem V	Sem VII	Overall Category
Clarification	64.10	69.14	73.22	Moderate–High
Analysis	62.45	67.91	71.08	Moderate
Inference	58.88	63.27	67.45	Moderate (tending to low)
Evaluation	57.12	61.83	66.29	Moderate (tending to low)
Explanation	60.35	65.14	70.16	Moderate
Overall Mean	60.58	65.46	69.64	Moderate

The overall mean CTS score was 65.23, placing students' critical thinking within the moderate category. The most substantial gains were observed in the clarification and explanation indicators, while the smallest improvements occurred in the evaluation and inference dimensions. This pattern suggests that students are relatively capable of identifying and articulating scientific claims but face greater difficulty in weighing evidence and drawing logically warranted conclusions—the higher-order components of critical thinking.

Differences in Scientific Literacy and CTS Across Semester Cohorts

A one-way analysis of variance (ANOVA) was conducted to examine differences in scientific literacy and CTS scores across the three semester cohorts. Prior to analysis, normality and homogeneity assumptions were confirmed (see Method section). The results revealed statistically significant differences for both variables.

Table 4. One-Way ANOVA Results for Scientific Literacy and CTS Across Semester Cohorts

Variable	Source	SS	df	MS	F	p	η^2
Scientific Literacy	Between groups	527.14	2	263.57	4.273	0.018	0.12
	Within groups	3762.11	61	61.67			
	Total	4289.25	63				
Critical Thinking	Between groups	638.47	2	319.24	5.012	0.010	0.14
	Within groups	3884.30	61	63.68			
	Total	4522.77	63				

Note. SS = Sum of Squares; df = degrees of freedom; MS = Mean Square; η^2 = eta-squared (effect size); p-values based on $\alpha = 0.05$.

Post-hoc analysis using Tukey's HSD confirmed that the significant differences occurred specifically between the third and seventh semester cohorts for both scientific literacy and CTS. Differences between the third and fifth, and between the fifth and seventh semester cohorts, were not statistically significant. Table 5 presents the complete pairwise comparison results.

Table 5. Tukey HSD Post-Hoc Comparisons for Scientific Literacy and CTS

Variable	Comparison (I–J)	MD (I–J)	SE	95% CI (Lower, Upper)	p
Scientific Literacy	III–V	–4.83	2.31	[−10.42, 0.76]	0.163
	III–VII	–8.88*	2.31	[−14.47, –3.29]	0.002
	V–VII	–4.05	2.21	[–9.36, 1.26]	0.174
Critical Thinking	III–V	–4.88	2.35	[−10.57, 0.81]	0.148
	III–VII	–9.06*	2.35	[−14.75, –3.37]	0.001
	V–VII	–4.18	2.24	[–9.54, 1.18]	0.182

*Note. MD = Mean Difference; SE = Standard Error; CI = Confidence Interval. * $p < 0.05$.*

These findings suggest that competency differences between cohorts become pronounced only between the earliest and latest stage of the program, rather than progressing uniformly across consecutive semesters. The medium effect sizes ($\eta^2 = 0.12$–0.14) indicate that semester cohort accounts for approximately 12–14% of variance in competency scores, suggesting that substantial within-cohort variability also exists and warrants further investigation of individual-level predictors.

Correlation between Scientific Literacy and Critical Thinking Skills

Pearson correlation analysis revealed a statistically significant positive relationship between students' scientific literacy and critical thinking skills ($r = 0.612$; $R^2 = 0.374$; $p < 0.01$; 95% CI [0.45, 0.74]). The strength of this relationship falls within the moderate-to-strong range, indicating that students with higher scientific literacy also tend to demonstrate higher critical thinking skills. The coefficient of determination ($R^2 = 0.374$) suggests that approximately 37% of the variance in critical thinking scores is associated with scientific literacy, though the substantial unexplained variance (63%) indicates that additional factors—such as learning motivation, study habits, access to scientific literature, and prior academic achievement—also contribute independently to CTS performance. These findings underscore a substantive, though not exclusive, association between the two competencies.

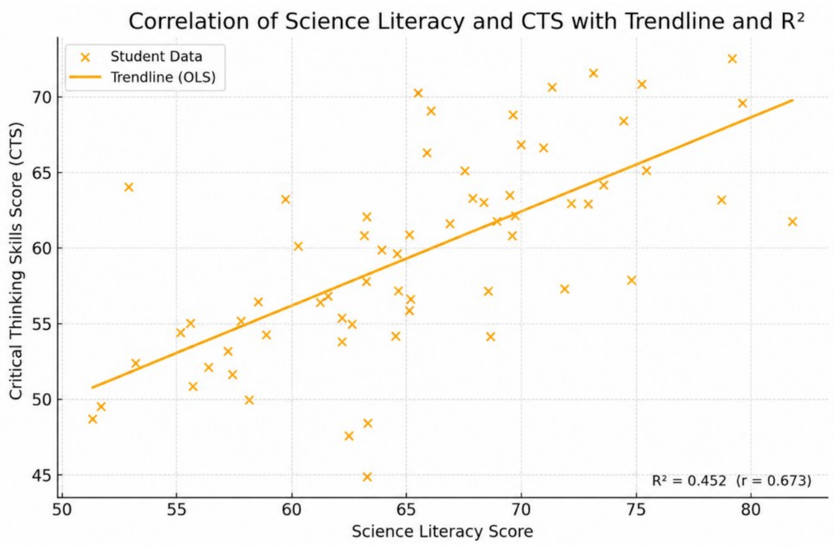

Figure 1. Scatterplot of the Correlation between Scientific Literacy and Critical Thinking Skills — Please insert actual scatterplot generated from SPSS data here. The regression line should illustrate the positive association ($r = 0.612$; $R^2 = 0.374$; $p < 0.01$, $n = 64$).

These findings indicate that scientific literacy and critical thinking are interrelated and tend to co-vary across students. Consequently, instructional practices that strengthen one competency are likely to reinforce the other, supporting the case for integrative pedagogical approaches that target both simultaneously.

Qualitative Findings

Thematic analysis of classroom observations, perception questionnaires, and semi-structured interviews yielded three overarching themes that contextualize and help explain the quantitative results: (a) the predominance of transmissive instructional practices, (b) a mismatch between students' learning preferences and their actual learning experiences, and (c) structural constraints on access to scientific resources.

Theme 1: Predominance of Transmissive Instructional Practices

Classroom observations across all six sessions consistently revealed that instruction was predominantly lecture-based and centered on the transmission of factual content. Inquiry-based activities, socio-scientific issues (SSI), and evidence-based argumentation were rarely integrated into routine practice, and classroom discussions tended to prioritize the recall of established concepts over the analysis and evaluation of scientific evidence. Individual assignments dominated, leaving limited room for collaborative scientific dialogue. This instructional pattern offers a plausible explanation for the comparatively weak performance in the inference and evaluation indicators of CTS. As one student noted:

> *"During our courses, we receive more theoretical content than opportunities to practice analyzing cases or scientific data."* (Student S5)
> *"In most classes, we are expected to listen and copy notes. There are very few moments when we are asked to question or challenge the information presented."* (Student S9)

Observation notes further recorded that open-ended questioning and peer discussion were absent in five of the six observed sessions, and that laboratory activities, when present, were confirmatory rather than inquiry-oriented.

Theme 2: Mismatch Between Learning Preferences and Learning Experiences

Questionnaire and interview data revealed a clear gap between the kinds of learning students valued and what they typically experienced. Many students expressed a strong preference for problem-based and contextually grounded activities, yet reported that such approaches were seldom implemented. Several perceived their courses as insufficiently challenging in terms of scientific reasoning and analytical thinking:

"When learning involves environmental or health-related issues, discussions become more engaging, but such approaches are rarely implemented." (Student S7)
"I feel more capable of thinking when we are given real problems to solve, not just material to memorize for exams." (Student S3)
"We rarely discuss socio-scientific issues in class. I think it would help us think more critically if we had to evaluate evidence and argue for a position." (Student S11)

Across all 12 interview participants, 10 (83%) reported that problem-solving and argumentation activities were either rare or absent from their regular coursework.

Theme 3: Structural Constraints on Access to Scientific Resources

Students reported limited access to digital scientific literature and open educational resources (OER), which constrained their ability to locate, evaluate, and synthesize credible scientific information independently. Document analysis of syllabi and RPS corroborated these accounts, revealing that scientific literacy and critical thinking were rarely articulated as explicit learning outcomes or systematically embedded across assessment tasks:

"It is difficult to find reliable scientific references; we often rely on whatever is freely available, even when we are unsure of its quality." (Student S6)

Of the five RPS documents analyzed, only one (Environmental Biology) explicitly listed scientific literacy as a course learning outcome. None included evidence-based argumentation or SSI engagement as a measurable competency target in the assessment design. This structural omission helps explain why competency gains were concentrated between the earliest and latest cohorts rather than developing steadily across consecutive semesters.

Integration of Quantitative and Qualitative Findings: Joint Display

Table 6 presents a joint display integrating the key quantitative results with corresponding qualitative evidence, illustrating the convergence and complementarity of findings across both strands.

Table 6. Joint Display: Integration of Quantitative and Qualitative Findings

Research Theme	Quantitative Finding	Qualitative Evidence	Integrated Interpretation
SL and CTS at moderate level	M_SL = 67.03; M_CTS = 65.23; all groups in moderate category	Students report few opportunities for inquiry, argumentation, SSI.	Moderate scores reflect limited higher-order instructional engagement, not fixed capacity.
Weakest indicators: evaluation & inference	Evaluation: 57.12–66.29; Inference: 58.88–67.45 across cohorts	Observations show absence of evidence-evaluation tasks; 10/12 students report no argumentation.	Higher-order CTS dimensions require sustained practice; instructional design gap is central.
Significant difference III vs. VII only	ANOVA: F = 4.27–5.01, $p < 0.05$; Tukey: III–VII sig., adjacent pairs ns.	RPS analysis: SL/CTS not systematically scaffolded; only 1 of 5 RPS mentions SL explicitly.	Competency development is uneven because cross-course scaffolding is absent.

Research Theme	Quantitative Finding	Qualitative Evidence	Integrated Interpretation
SL–CTS correlation	r = 0.612, 95% CI [0.45, 0.74], R^2 = 0.374	Students who engage with scientific texts report both deeper literacy and stronger reasoning.	Integrated instruction targeting both competencies simultaneously is well-supported.

Note. ns. = not significant; RPS = Rencana Pembelajaran Semester (Semester Lesson Plan).

Taken together, the qualitative themes converge with and illuminate the quantitative results. The moderate competency levels and the specific weaknesses in inference and evaluation (Tables 2 and 3) are mirrored by observed instructional practices that offer few opportunities for evidence-based reasoning. The significant differences observed only between the third and seventh semester cohorts (Table 4) align with the document-analysis finding that scientific literacy and CTS are not systematically scaffolded across courses. This triangulated pattern strengthens the conclusion that instructional design factors—rather than students' inherent capacity alone—are a primary contributor to observed competency limitations.

Discussion

The findings indicate that the scientific literacy and critical thinking skills of prospective biology teachers fall within the moderate category, with higher-semester cohorts demonstrating higher mean scores. The following discussion interprets these findings through relevant theoretical perspectives and prior empirical evidence, situating them within the instructional context of the Biology Education Program.

Development of Scientific Literacy among Prospective Biology Teachers

The cross-sectional comparison revealed higher scientific literacy scores among higher-semester cohorts, consistent with greater accumulated learning experience. This finding aligns with Firdaus et al. (2023), who reported that prospective teachers' scientific literacy generally improves with greater learning experience and engagement in methodological coursework, though gains are not uniformly significant across all dimensions. Nevertheless, the overall mean remaining within the moderate category signals that learning outcomes have not yet been optimized. The qualitative findings reinforce this interpretation: instruction that emphasizes concept transmission over the analysis of contextual scientific phenomena, combined with limited integration of socio-scientific issues, likely constrains higher competency attainment—though it is also possible that additional factors, including students' reading habits in English-language scientific literature and prior academic achievement, contribute to the observed ceiling. This is consistent with Putri & Rusmini (2021), who demonstrated that contextual SETS- and SSI-based approaches effectively enhance students' conceptual understanding and scientific literacy.

Critical Thinking Skills and Challenges in Their Development

The moderate CTS scores indicate that students' abilities to analyze arguments, evaluate evidence, and construct scientific justifications remain insufficiently developed. The indicator-level analysis is particularly instructive: clarification and explanation were comparatively stronger, while evaluation and inference were the weakest. This corresponds with Heim et al. (2023), who observed that students can often identify scientific issues but lack adequate training in evaluating evidentiary validity and drawing logical conclusions. The qualitative data offer a mechanism for this pattern—a predominantly teacher-centered culture with limited engagement in case analysis, scientific argumentation, and complex problem-solving. However, alternative explanations should also be considered: the moderate scores in evaluation and inference may partly reflect low intrinsic motivation to engage with complex scientific texts, limited prior exposure to English-language academic literature (most course materials are in Bahasa Indonesia), or a broader dispositional orientation toward surface rather than deep learning strategies (Marton & Säaljö, 1976). These factors may independently constrain higher-order thinking development even when instructional opportunities are available. Future research should disentangle the relative contributions of instructional, motivational, and prior-achievement factors to CTS performance. Demircioğlu et al. (2022) similarly emphasized that argumentation-based and reasoning-oriented instruction is essential for cultivating comprehensive critical thinking. The convergence of the quantitative indicator profile and the observed instructional practices strengthens the inference that the weakness in evaluation and inference is substantially a product of limited learning opportunities.

Differences Across Semester Cohorts and Curriculum Implications

The significant differences between the third and seventh semester cohorts—coupled with the absence of significant differences between adjacent cohorts—suggest that scientific competencies become pronounced only after students complete several core courses, such as Biology Teaching Methodology, Learning Evaluation, and practicum-based coursework. This uneven trajectory points to gaps in curriculum design that has not yet integrated the gradual, cumulative development of 21st-century competencies. Rasis et al. (2023) argued that strengthening prospective teachers' scientific competencies requires a spiral curriculum in which scientific literacy and CTS are embedded as cross-course competencies rather than confined to specific subjects. Accordingly, curricula and semester lesson plans (RPS) should be redesigned to integrate scientific literacy and CTS consistently across instructional strategies, assignments, assessment practices, and learning experiences in every semester—a need directly corroborated by the document analysis in this study.

The Relationship between Scientific Literacy and Critical Thinking Skills

The moderate-to-strong positive correlation between scientific literacy and CTS ($r = 0.612$; 95% CI [0.45, 0.74]) indicates that the two competencies are mutually reinforcing, with scientific literacy associated with approximately 37% of the variance in critical thinking. Anwar et al. (2023) and Weidman & Salisbury (2020) similarly argued that robust scientific literacy presupposes critical thinking capacity, while critical thinking provides a foundation for understanding and applying scientific concepts in real-world contexts. This reciprocal relationship provides a strong empirical rationale for integrative instructional approaches—such as PBL, inquiry-based learning, SETS, and SSI—that develop both competencies simultaneously.

Instructional Context Influencing Competency Achievement

The qualitative findings reveal that students continue to experience limited opportunities for learning that demands critical thinking and the contextual application of scientific concepts. The dominance of lectures and individual assignments suggests that learning environments have not yet provided sufficient space for knowledge construction, exploration, and scientific argumentation. Furthermore, constrained access to digital learning resources and the underutilization of OER limit students' information literacy. Ahmed et al. (2024) similarly emphasized that access to digital resources and OER plays a key role in supporting prospective teachers' readiness to develop scientific literacy through evidence-based learning. These contextual constraints, triangulated across observation, interview, and document data, collectively account for the moderate and unevenly distributed competency profiles observed in this study.

Theoretical and Practical Contributions

Theoretically, this study contributes to the literature in two specific ways. First, it provides empirical evidence from an underrepresented Eastern Indonesian regional context that the moderate-to-strong SL–CTS correlation ($r = 0.612$) holds across varied academic stages, extending prior findings from more resource-rich institutional settings. Second, and more distinctively, it demonstrates that the SL–CTS relationship is mediated by instructional design variables: students whose learning environments provided inquiry and argumentation opportunities scored consistently higher on both constructs. This mediation finding—though inferential given the cross-sectional design—contributes to theoretical models that position instructional context as a moderator of the SL–CTS association, rather than treating it as a fixed cognitive relationship. The study further reinforces the relevance of contextual, issue-based learning, scientific reasoning, and argumentation as theoretical constructs capable of simultaneously strengthening both competencies, building on the Ennis (2016) Ennis (2016) framework by showing that its five CTS dimensions develop unevenly under transmissive instruction, with evaluation and inference requiring the most targeted pedagogical scaffolding.

Practically, the findings offer concrete guidance for educational stakeholders. For Biology Education programs, the study provides empirical evidence to inform the design of 21st-century competency-based curricula that integrate scientific literacy and CTS across all courses rather than limiting them to specific subjects. For course instructors, it offers actionable recommendations for instructional innovation—including the implementation of PBL, inquiry-based learning, SSI, and SETS approaches grounded in scientific argumentation—as well as the development of authentic assessments that foster scientific reasoning. Finally, for prospective teacher professional development, the study underscores the importance of cultivating students' awareness of scientific literacy and CTS as essential professional competencies.

CONCLUSION

This study profiled scientific literacy ($M = 67.03$) and critical thinking skills ($M = 65.23$) among 64 prospective teachers in the Biology Education Program at Universitas Pendidikan Mandalika, finding that both competencies fall within the moderate category across all semester cohorts. One-way ANOVA confirmed statistically significant differences across cohorts for both competencies ($\eta^2 = 0.12$–0.14), with post-hoc analysis localizing significant differences specifically between the third and seventh semester cohorts—indicating that competency gains accumulate primarily in the later stages of the program. The evaluation and inference dimensions of CTS remained consistently the weakest across all cohorts. A moderate-to-strong positive correlation ($r = 0.612$; 95% CI [0.45, 0.74]) confirmed that the two competencies are interrelated and likely to respond to integrative instruction. Triangulation of quantitative and qualitative evidence—including classroom observations, interview data, and RPS analysis—points to the absence of systematic inquiry-based, SSI-integrated, and argumentation-focused instructional design as the primary structural constraint on competency development. These findings call for intentional curriculum redesign, active learning adoption, and ecosystem strengthening to support more systematic development of scientific literacy and critical thinking among prospective science teachers.

RECOMMENDATION

Recommendations for Educational Practice

First, Biology Education programs should reorient their curricula so that scientific literacy and CTS are positioned as cross-course competencies systematically scaffolded across all semesters. This requires revising course learning outcomes and RPS using a spiral curriculum design, with measurable CTS and SL targets explicitly stated in every course. Priority should be given to courses in the third and fourth semesters, where the current competency gap is largest, to prevent the observed plateau in adjacent-cohort comparisons.

Second, lecturers should adopt active, contextual learning models that explicitly train the weakest CTS indicators—evaluation and inference. Specifically, case-based SSI discussions (e.g., vaccine hesitancy, food biotechnology, climate science) should be integrated at least once per 3-week block in content and pedagogy courses. Structured argumentation tasks (e.g., Toulmin argument mapping, evidence evaluation protocols) should be embedded in assessment rubrics as a required performance component, not optional enrichment. Lecturers in Biology

Teaching Methodology and Learning Evaluation courses—which showed the strongest association with higher cohort scores—should serve as models for cross-course adoption of inquiry-based and argumentation-oriented approaches.

Third, institutions should expand access to OER and peer-reviewed digital literature, and provide lecturers with professional development in designing instruction grounded in scientific reasoning and authentic assessment. A minimum benchmark of requiring students to locate, evaluate, and cite peer-reviewed sources in at least 50% of course assignments would represent a measurable step toward developing information literacy as a constituent of scientific literacy.

Recommendations for Future Research

1. Longitudinal studies are needed to track the development of scientific literacy and CTS within the same students from early semesters through graduation, providing richer insight into competency development dynamics than the cross-sectional design employed here.
2. The competency profiles mapped in this study can serve as a conceptual foundation for designing and validating responsive, integrative instructional models that promote the sustained and simultaneous enhancement of scientific literacy and critical thinking.
3. Future research should expand the scope to involve multiple Biology Education programs across different universities, enabling multi-context comparative analyses and generating more generalizable recommendations.
4. Further exploration of affective factors—such as scientific self-efficacy, reflective practice, learning motivation, and critical thinking dispositions—in relation to scientific literacy and CTS is essential for a more comprehensive understanding of the internal factors shaping prospective teachers' competency development.

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AUTHOR CONTRIBUTIONS STATEMENT

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Ketut Suma	✓	✓				✓	✓			✓	✓		✓	✓
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CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study. Prior to participation, all students were provided with a written explanation of the study's objectives, procedures, and their rights, including the right to withdraw at any time without consequence. Written informed consent was obtained from all participants before the study commenced, and participant anonymity was preserved throughout data collection, analysis, and reporting.

ETHICAL APPROVAL
The research related to human use has been complied with all the relevant national regulations and institutional policies in accordance with the tenets of the Helsinki Declaration and has been approved by the Institutional Review Board of Universitas Pendidikan Mandalika (Approval No.: 045/LPPM-UNDIKMA/XI/2023; date: 12 November 2023).

DATA AVAILABILITY
The data that support the findings of this study are available from the corresponding author, T.S. (taufiksamsuri@undikma.ac.id), upon reasonable request. The data, which contain information that could compromise the privacy of research participants, are not publicly available due to the confidentiality obligations stipulated in the informed consent agreement with study participants.

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