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ENHANCING BIOLOGY STUDENTS' SCIENTIFIC LITERACY THROUGH THE CRITICAL ANALYSIS AND DISCUSSION-COMPARISON WITH THE EXTENDED LEARNING COMMUNITY MODEL

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ABSTRACT

Despite global reforms in science education that emphasize collaboration, critical thinking, and real-world application, many secondary students continue to struggle with scientific reasoning and communication, particularly in Biology. This study addresses this gap by evaluating the effectiveness of the Critical Analysis and Discussion Comparison with Extended Learning Community (CADC-ELC) method in enhancing students' written and oral communication and cognitive performance. Employing a quasi-experimental design with 90 tenth-grade students in Indonesia, participants were divided into three groups: CADC-ELC, CADC-only, and conventional instruction. Data were collected using validated observation sheets and a 30-item cognitive test and analyzed using the Games-Howell post-hoc test. Results revealed that CADC-ELC significantly outperformed other groups in all areas: written communication improved from M = 31.0 to 70.3, oral communication from M = 9.1 to 17.06, and cognitive scores from M = 33.3 to 83.1 (all $p < .001$). These findings suggest that CADC-ELC offers a robust, globally relevant model for strengthening science education through dialogic, scaffolded, and context-rich instruction.

Keywords: critical analysis; extended learning community; discussion-comparison method

INTRODUCTION

Globally, science education is undergoing a fundamental transformation, with an increasing emphasis on student-centered, collaborative, and contextual learning environments that nurture both scientific reasoning and communication. These approaches stand in contrast to conventional, teacher-dominated instruction that often limits critical engagement and interdisciplinary thinking. In response, many national curricula have adopted frameworks that prioritize inquiry, dialogue, and knowledge co-construction among students, teachers, and the wider community. Indonesia's Independent Curriculum reflects this pedagogical evolution by promoting extended learning communities (ELCs) that incorporate external experts to contextualize academic content and bridge the gap between classroom learning and real-world challenges (Bunnaen et al., 2022; Khasawneh et al., 2023). Such approaches are particularly valuable in subjects like Biology, where students must connect abstract concepts with complex natural systems (Gilissen et al., 2021; Sabrina et al, 2024). The involvement of community practitioners in the learning process enhances relevance and supports student engagement in authentic problem-solving, discourse, and collaborative learning.

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The urgency of strengthening science education is further underscored by the United Nations Sustainable Development Goals (SDGs), particularly SDG 4 (Quality Education) and SDG 17 (Partnerships for the Goals), which emphasize equitable, high-quality learning and school–community collaboration. Indonesia's consistently low performance in international science assessments underscores a pressing need for pedagogical innovations to build scientific literacy. PISA data place Indonesia among the bottom 10 of 79 participating countries, with science scores averaging nearly 100 points below the OECD mean (Hamzah et al., 2023), indicating systemic weaknesses in both cognition and communication, two pillars of scientific literacy.

Despite these progressive reforms, many secondary students, particularly in low- and middle-income countries, continue to underperform in foundational academic skills. Indonesia, for instance, ranks among the bottom 10 of 79 countries in international science and reading assessments, with achievement levels significantly below the ASEAN average (Hamzah et al., 2023). These global benchmarks highlight widespread challenges in cognitive development and science literacy, which are often compounded by fragmented curricula and outdated teaching practices. Research indicates that Indonesian high school students particularly struggle in Biology, frequently failing to demonstrate conceptual understanding or apply knowledge across contexts (Yanti et al., 2024). Furthermore, scientific literacy depends not only on cognition but also on communication, yet students often exhibit limited competence in writing and speaking, essential tools for articulating scientific understanding.

Preliminary studies conducted in Indonesian classrooms further reveal that discussion-based instruction tends to be superficial, with students rarely engaging in higher-order questioning, argumentation, or collaborative meaning-making (Maridi et al., 2019; Irwandi, 2020a). These findings reinforce the need for pedagogical models that integrate communication, cognition, and authentic learning experiences in a coherent instructional design.

Deficiencies in communication skills are not unique to Indonesia but resonate globally. Numerous studies highlight how students across various contexts exhibit weak written communication, characterized by superficial reasoning, structural disorganization, and inaccurate language use, issues closely tied to rote instructional methods and minimal exposure to authentic writing tasks (Hamia et al., 2021; Nilam & Yenti, 2023; Bolat et al., 2024). Scholars have argued that writing in science is a cognitively demanding activity requiring sustained practice, logical reasoning, and content mastery. Similar issues plague oral communication: students are often reluctant to speak in class due to fear of error, lack of confidence, and disengagement, challenges reported in both developing and developed educational systems (Angganing et al., 2022; Putri et al., 2023; Febriyanto et al., 2024). Even the increasing use of digital tools has not reversed this trend; instead, overreliance on passive media consumption may further reduce students' dialogic engagement (Indriayu et al., 2018; Ueda et al., 2023). Classroom observations have consistently found minimal levels of questioning, peer interaction, or meaningful oral exchanges in science education (Ningsih et al., 2017; Maridi et al., 2019).

Nonetheless, despite extensive scholarship on collaborative learning and critical analysis, much of which focuses on tertiary education, there remains a distinct gap in how integrative models operate in secondary science contexts. Published studies in internationally indexed journals, including CBE–Life Sciences Education, JPII, and the Asia-Pacific Journal of Education, reveal three major gaps: (1) existing discussion methods often yield limited gains in communication skills (Orawiwatnakul & Wichadee, 2016; (2) extended learning communities have rarely been empirically tested in secondary Biology. Irwandi et al., 2024); and (3) critical analysis is predominantly studied with university students, with little evidence at the high school level (Susilo et al., 2018; Bilki & Irgin, 2022). This gap analysis indicates a lack of integrated, multi-component interventions that simultaneously address cognition, writing, and oral communication within authentic, community-linked learning environments.

Departing from this gap, the present study focuses on the Critical Analysis and Discussion-Comparison with the Extended Learning Community (CADC-ELC) model as an innovative pedagogical framework that merges structured critique, dialogic interaction, and practitioner engagement. This study aims to support and extend previous findings in tertiary settings by testing whether CADC-ELC can produce measurable improvements in secondary education, thereby addressing a critical blind spot in current literature.

Operationally, this study aims to: (1) determine whether the CADC-ELC model yields statistically significant gains in students' written communication, (2) evaluate its impact on oral communication, and (3) examine whether it improves cognitive learning outcomes in Biology. These objectives contribute directly to the development of science education by offering empirically tested strategies aligned with SDG 4 and SDG 17. The novelty of this research lies in applying a multi-layered, dialogic-constructivist model, previously confined to university contexts, to high school Biology, thereby testing its potential to correct gaps identified in existing studies and provide new evidence for scalable, community-integrated science pedagogy According to Oktaviani & Faizah (2024), the capabilities associated with scientific literacy involve utilizing scientific understanding to address challenges, pinpoint inquiries, and formulate judgments grounded in evidence regarding the environment and how it is altered through human actions. This can be conducted through academic written or oral communication.

To explore the global applicability of CADC-ELC in addressing core science education challenges, this study addresses the following research questions: (1) Does the CADC-ELC method significantly improve students' written communication skills in Biology learning? (2) Does the CADC-ELC method significantly improve students' oral communication skills in Biology learning? (3) Does the CADC-ELC method significantly improve students' cognitive abilities in Biology learning?

Among widely adopted instructional strategies to improve students' communication and reasoning skills is the discussion method. Frequently positioned as an interactive, student-centered pedagogy, it is often assumed to stimulate critical thinking and verbal participation. However, emerging evidence suggests that these assumptions do not always hold, particularly within the context of secondary science education. Several empirical studies have questioned the efficacy of discussion-based methods in yielding measurable improvements in student outcomes. Orawiwatnakul and Wichadee (2016) found that small-group discussions had a negligible impact on students' speaking abilities or learning satisfaction. Likewise, there were no statistically significant gains in oral communication skills following structured group discussions in the Philippines. Digital adaptations of discussion-based instruction have not fared better; Murphy et al. (2021) observed students' preference for asynchronous text-based platforms over video discussions, raising questions about the modality's capacity to foster dialogic competence. Pradana et al. (2024) added to these concerns by demonstrating that online discussion forums, even when gamified, failed to increase student participation, suggesting that surface-level engagement is often mistaken for meaningful academic discourse.

Moreover, the effectiveness of discussion methods appears to vary by demographic and contextual factors. Omovie & Kpangban (2023) identified a gendered pattern in classroom participation, with female students more likely to engage verbally. Jatau et al. (2021) proposed that discussion methods may narrow gender gaps in Biology learning, although such gains remain inconsistently reported. In another study, Paine and Knight (2020) found no significant improvement in reasoning skills attributable to discussion strategies. Even when compared with other teaching modalities, such as demonstration, discussion methods only marginally outperformed alternatives (Cleopas & Igbojinwaekwu, 2024). While theoretical models describe discussion as a tool for collaborative knowledge building and verbal expression (Chen, 2019), these pedagogical promises often go unrealized in secondary classrooms where interactions remain teacher-directed and formulaic.

Conventional learning has often been considered ineffective because it tends to be teacher-centered rather than student-centered. The most commonly used method is a one-way lecture, which limits direct interaction between teachers and students and prevents improvement in students' communication skills. However, the effectiveness of deep learning in schools remains limited, and teachers still struggle to design and implement learning due to limited training (Zafirah et al., 2025). Furthermore, sufficient resources such as technology and facilities are not yet fully available. As a result, expected competencies, such as student communication skills, cannot develop properly. In deep learning applications, when teachers engage students in meaningful discussions, effective communication among students can improve student learning outcomes (Qohar & Widyaningrum, 2025).

As critiques of traditional discussion methods grow, the educational community has turned to more integrative, socially embedded approaches, chief among them, the extended learning community (ELC) model. ELCs promote partnerships between schools and external experts, enabling students to contextualize academic content and develop skills through real-world applications. This model aligns with constructivist and socio-cultural learning theories that emphasize the importance of situated knowledge and authentic practice (Nithideechaiwarachok & Chano, 2024; Zhu et al., 2024; Sreelohor et al., 2025)

Initial findings on ELCs are encouraging. Sabrina et al. (2024) reported increased student motivation and teacher engagement when parents and community figures were embedded in the learning process. Firdaus (2018) found that interactions with external professionals enabled students to gain new perspectives, thereby enhancing their understanding of complex topics. These benefits align with broader international literature indicating that community-engaged learning fosters interdisciplinary thinking, academic resilience, and social capital (Jarupongputtana et al., 2022; Kee et al., 2025; Matthews et al., 2025).

However, research on ELCs remains uneven. Much of the literature has focused on early childhood or tertiary education, with limited exploration of their effects on secondary students' core academic competencies. For instance, Suweleh et al. (2024) demonstrated positive oral communication outcomes in early education settings, though without community involvement. Irwandi et al. (2024) documented increased student activity among university students participating in learning communities, but did not address secondary-level applications or cognitive outcomes. Moreover, many studies rely on perception surveys or theoretical models rather than empirical classroom data (Lubis et al., 2022; Dzul et al., 2023). While student satisfaction and teacher collaboration are frequently highlighted (Geary et al., 2023; Khasawneh et al., 2023), few investigations have rigorously examined whether ELCs improve writing proficiency, verbal articulation, or scientific reasoning, especially in science subjects such as biology.

In parallel, critical analysis has emerged as a promising instructional method for fostering higher-order thinking and academic communication. Unlike conventional assignments that prioritize rote memorization, critical analysis tasks require students to evaluate evidence, interrogate assumptions, and synthesize multiple viewpoints, which are the skills central to scientific inquiry and academic discourse. A growing body of literature confirms the pedagogical value of critical analysis. Susilo et al. (2018) demonstrated that university students who engaged in structured critique of scholarly articles improved their ability to formulate research questions and academic arguments. Fitriani et al. (2024) found that critical analysis significantly enhanced the cognitive development of pre-service Biology teachers. Bilki and Irgin (2022) similarly noted gains in reading comprehension and argumentative writing among English language learners following intensive critical analysis instruction. Moreover, Irwandi & Hasan (2021) reported increased questioning behavior and peer interaction among university students, suggesting that critical analysis fosters dialogic and metacognitive skills.

Despite these successes, most existing research is confined to tertiary education. The application of critical analysis in secondary classrooms, particularly in science education, remains underexplored. High school students differ significantly from university learners in terms of cognitive development, motivation, and autonomy (Putra, 2019; Younis, 2024). As such, pedagogical strategies proven effective at the university level may require adaptation to meet the developmental needs of adolescent learners. The lack of empirical data on how critical analysis operates in high school settings, particularly when integrated with other methods, constitutes a major gap in the literature.

Recognising the limitations of single-method instruction, recent scholarship has advocated integrated pedagogical models that blend critical thinking, structured discourse, and contextualized learning. The Critical Analysis and Discussion Comparison with Extended Learning Community (CADC-ELC) model represents one such innovation. It merges the analytical rigor of critical evaluation with the social dynamics of structured discussion and the real-world applicability of community-based engagement. Theoretically, it draws on multiple traditions, involving constructivism, dialogic learning, and situated cognition, to foster a multidimensional learning experience.

Empirical evidence on the CADC-ELC method remains limited but promising. Irwandi (2020a) and Irwandi & Hasan (2021) documented improvements in critical thinking, peer collaboration, and academic communication among university students exposed to this model. Cassandra et al. (2024) reported positive outcomes in scientific writing within teacher education programs using CADC-ELC. These findings suggest that integrating multiple instructional components rather than relying on a single method may yield synergistic gains in learner outcomes.

Nevertheless, all documented implementations of CADC-ELC have been restricted to tertiary-level learners. There is currently no empirical research assessing its effectiveness in high school contexts, particularly in content-heavy and conceptually demanding subjects like Biology. This lack of evidence represents a substantial blind spot, especially considering that secondary students often lack the cognitive maturity, academic confidence, and communication skills needed to thrive in traditional instructional settings. Investigating whether CADC-ELC can support these learners' development is thus both timely and essential.

The CADC-ELC model is underpinned by a dialogic-constructivist pedagogical framework that views learning as an active process of knowledge construction facilitated by language, social interaction, and engagement with real-world contexts. Rather than treating cognition, communication, and content knowledge as discrete components, this paradigm recognizes their mutual reinforcement within scaffolded, collaborative learning environments. Three interrelated theoretical strands provide the foundation for this approach: dialogic learning theory, situated cognition, and social constructivism. Dialogic learning theory emphasizes the co-construction of meaning through dialogic exchanges, in which learners engage in thoughtful, reasoned discussion that builds on others' ideas and challenges assumptions. As asserts, meaningful learning emerges not merely through verbal participation but through sustained, purposeful dialogue that encourages metacognitive awareness and deep understanding. Within the CADC-ELC framework, structured peer critiques and group comparisons serve as dialogic mechanisms, enabling students to articulate, negotiate, and refine their ideas in interaction with others. These interactions cultivate fluency in academic communication while fostering critical reflection.

Complementing this is situated cognition theory, which posits that learning is context-dependent and best understood when embedded in authentic practice. Zhao et al. (2025), Xiaotian et al. (2024), and Wang et al. (2025) argue that abstract knowledge remains inert unless anchored in real-world experiences. By integrating practitioners from outside the classroom, the CADC-ELC model situates scientific learning within the contexts in which it is applied, thereby enhancing its relevance and cognitive accessibility. Through practitioner-led discussions and real-world case analyses, students are encouraged to bridge disciplinary knowledge with societal issues, a skill increasingly valued in global science education. The third theoretical pillar is the social constructivism of Kusmaryono et al. (2021) and Indriayu (2025), particularly the concept of the Zone of Proximal Development (ZPD), which holds that learning occurs most effectively when more knowledgeable peers or mentors support students. In the CADC-ELC setting, the ZPD is activated through scaffolded interactions among students, teachers, and community experts. These actors collaboratively guide learners from surface-level participation to more autonomous and conceptually rich engagement, promoting both cognitive growth and communication competence.

In essence, these theoretical perspectives justify the integrated design of CADC-ELC as a holistic pedagogy. They converge on the premise that reasoning, communication, and content mastery are deeply intertwined competencies that must be cultivated through socially mediated, context-rich, and dialogically oriented instruction. As Mercer & Howe (2012) and Asterhan et al. (2015) emphasize, such conditions not only enhance individual academic performance but also prepare students to engage meaningfully in scientific and civic discourse. Within this framework, CADC-ELC offers a pedagogical architecture that addresses the interrelated challenges of cognition, communication, and relevance in contemporary secondary science education. Figure 1 illustrates the synergy of dialogic-constructivist pedagogy implemented in the study.

Figure 1. Illustration of the Synergy of Dialogic-Constructivist Pedagogy

METHODS

Grounded in the dialogic-constructivist framework outlined previously, this study employed a quasi-experimental, nonequivalent control group design (Gay et al., 2012) to evaluate the effects of the CADC-ELC pedagogical model on students' written and oral communication and cognitive learning outcomes in secondary Biology education. This approach aligns with theoretical perspectives that emphasize authentic, context-rich, and socially mediated learning environments (Hidayati et al., 2023; Stefaniak et al., 2025) and operationalizing them through rigorous experimental methodology. The use of intact classes, rather than randomized individual assignment, reflects both ethical and practical constraints within the school setting while preserving ecological validity. The design enabled systematic comparison between pre-test and post-test results across three instructional conditions: CADC-ELC, CADC-only, and conventional teaching.

To provide clear research stages as recommended in educational design literature, this study followed four main stages: (1) preparation and instrument validation, (2) pre-testing, (3) implementation of treatments, and (4) post-testing and data analysis. Each stage is elaborated in Table 1 to ensure methodological transparency and replicability.

Table 1. Research Design Framework

Group	Pre-Test (O_1)	Treatment (X)	Post-Test (O_2)
Experiment 1	O_1	X_1 (CADC-ELC)	O_2
Experiment 2	O_1	X_2 (CADC only)	O_2
Control	O_1	X_3 (Conventional)	O_2

(Gay et al., 2012)

O_1 represents the pre-test given before the treatment, while O_2 represents the post-test given after the treatment is completed. The treatments provided consist of three types of interventions: X_1, the CADC-ELC model (Critical Analysis and Discussion enriched with Advanced Learning Community involvement); X_2, CADC involving only Critical Analysis and Discussion without an external community component; and X_3, conventional learning that does not involve critical analysis or external community involvement. This structure allows researchers to more comprehensively compare the effectiveness of each approach.

This research was conducted with existing classes, using both an experimental and a control group, because it was not possible to assign subjects randomly. If the subjects were randomly selected, it could disrupt the school system or the school's conditions. The population of this study comprised all 150 grade 10 students at SMA Negeri 7 Bengkulu (5 classes). The samples were collected from three classes (2 experimental and one control), totalling 90 students. The decision on the experimental and control classes was made randomly.

The independent variables were the instructional methods (CADC-ELC, CADC-only, and conventional), and the dependent variables were students' written communication, oral communication, and cognitive achievement in Biology.

The study population comprised 150 tenth-grade students from five classes at SMA Negeri 9 Bengkulu. Employing stratified random sampling, three classes were selected (total n = 90): one for the CADC-ELC group, one for CADC-only, and one for the control condition. This sampling method minimized selection bias while preserving the integrity of natural classroom groupings, consistent with situated cognition theory's emphasis on learning in authentic social settings (Brown et al., 1989). Group equivalence was established using baseline pre-test scores across all outcome variables prior to the intervention. Before the intervention, demographic characteristics, prior academic performance, and baseline communication scores were reviewed to ensure group comparability. This preliminary review follows the recommendation for strengthening internal validity in quasi-experiments.

The writing, oral, and cognitive skills instruments were first piloted on 30 students from both experimental and control classes. Criterion validity was assessed using the Pearson correlation coefficient, with values approaching +1 indicating a strong positive correlation, -1 indicating a strong negative correlation, and 0 indicating no significant correlation. (Bushmakin & Cappelleri, 2022). To test reliability, we used Cronbach's Alpha because the instrument uses a Likert Scale, with a Cronbach's Alpha value ranging from 0 to 1; values> 0.70 indicate good internal consistency (Subhaktiyasa, 2024). The overall instrument validity was 0.722 (Pearson's r), and the reliability was 0.941 (Cronbach's alpha), indicating that the instruments were valid and reliable.

Three validated instruments were used, reflecting the study's multidimensional focus on both communication and cognition. All instruments were subjected to expert validation by biology educators and educational measurement specialists, followed by small-scale pilot testing to ensure clarity, reliability, and construct validity.

Students' critical analysis outputs were assessed on content relevance, structural organization, and language accuracy (Faurisiawati & Supeno, 2022; Anwar et al., 2020). A four-point Likert scale (1 = Poor, 4 = Very Good) generated scores scaled from 0–100, interpreted via an absolute scale: A (80–100%), B (60–79%), C (40–59%), D (20–39%), E (<20%) (Zainul, 2018).

Performance in classroom discussion was rated on the ability to formulate questions, express opinions, present ideas, listen actively, and respond to peers (Budiono & Abdurrohim, 2020). The same four-point scale and grading rubric as for written communication were used, ensuring evaluation consistency across modalities. Observation procedures were standardized using a structured protocol to maintain consistency across sessions.

A 30-item multiple-choice assessment covering Bloom's taxonomy levels C1–C6 was adapted from the official 2024 curriculum and focused on Ecosystem Interactions, Food Chains and Webs, Biogeochemical Cycles and Succession, and Conservation. Items were drawn from the national Professional Development Module for SMA Biology Zaenal Arifin, M.Si. https://cdn-gbelajar.simpkb.id/s3/p3k/Biologi/Perpembelajaran/BIOLOGI-PB7.pdf PKB or Continuing Professional Development (CPD), a Module for Biology for Senior High School, Competency Group (Zaenal Arifin, M.Si.). Scores were converted to a 0–100 scale using the same grading standards as above.

Reflecting the dialogic-constructivist underpinnings of the CADC-ELC model, the intervention spanned four weekly meetings, each consisting of three 50-minute instructional hours, totalling 150 minutes per session. Across four meetings, students received 600 minutes (10 hours) of instruction in both the experimental and control conditions, ensuring parity in instructional time.

Each CADC-ELC meeting was structured around three stages, including Introduction, Main Activity, and Closure, integrating dialogic learning, situated cognition, and social constructivist scaffolding:

Stage 1 – Introduction (Preparation): Teachers outlined objectives and strategies; external practitioners introduced themselves and contextualized the lesson by connecting prior knowledge to real-world applications.

Stage 2- Main Activity (Interaction): Teachers and practitioners jointly facilitated the lesson. Student groups presented their critical analyses, designated comparison groups, and then critiqued them through structured peer discussion and rebuttal.

Stage 3 - Closure (Consolidation): Students synthesized the outcomes of the group discussion and reflected collectively on their learning. Teachers conducted evaluations and provided targeted guidance for further inquiry.

The control class also participated in four meetings of equal length but followed conventional instructional routines without explicit integration of critical analysis, dialogic discussion, or practitioner engagement.

Table 2. Syntax of CADC-ELC Learning Model

Stage	Activities
Introduction	The teacher and practitioner introduce objectives and real-world relevance; activate prior knowledge.
Main Activity	Collaborative teaching; critical analysis presentation; peer critique; group rebuttal; dialogic discussion; feedback from teacher and practitioner
Closure	Student synthesis of learning outcomes; teacher-led reflection and evaluation

All quantitative data were analyzed using SPSS Version 26 for Windows. Prior to hypothesis testing, assumption checks were performed to determine data normality and variance homogeneity. The Kolmogorov–Smirnov test indicated that the data violated the normality assumption, while Levene's test confirmed homogeneity of variances. Given the non-normal distribution and unequal sample variances, the Games–Howell post-hoc test was selected for inferential analysis. This robust non-parametric test is suitable for comparing multiple groups under heteroscedastic conditions (Ghozali, 2001). The test was applied to identify statistically significant differences among the three instructional groups across all dependent variables: written communication, oral communication, and cognitive learning outcomes. Effect sizes (Cohen's d) were also calculated to estimate the magnitude of the differences, providing insight into the intervention's practical significance beyond statistical results.

RESULTS AND DISCUSSION

Table 3 presents descriptive statistics for students' written communication scores on the pre-test and post-test across the three instructional groups.

Table 3. Written Communication Skills – Pre-test and Post-test Averages

Group	Pre-test (0–100)	Category	Post-test (0–100)	Category
CADC-ELC	31	Poor	70.3	Excellent
CADC	30.9	Poor	56.2	Good
Control	32.4	Poor	42.3	Moderate

As shown in Table 3, written communication scores differed substantially among the three groups after the intervention. A visual comparison of gain scores would show the CADC-ELC group improving by 39.3 points, nearly three times the increase observed in the CADC-only group (25.3 points) and more than five times that of the control group (9.9 points). If represented in a bar chart, the CADC-ELC bar would stand markedly higher, illustrating the strongest treatment effect. At pre-test, all groups were categorized as "poor," with similar mean scores: CADC-ELC (M = 31.0), CADC (M = 30.9), and Control (M = 32.4). Following the intervention, however, the CADC-ELC group reached an "excellent" level (M = 70.3), the CADC group improved to "good" (M = 56.2), and the control group showed only a modest increase to "moderate" (M = 42.3), accentuating the greater effectiveness of the integrated CADC-ELC model.

To determine whether the observed mean differences were statistically significant, the Games–Howell post-hoc test results are presented in Table 4.

Table 4. Games-Howell Post-Hoc Comparison – Written Communication

Comparison	Mean Difference	Std. Error	Sig. (p)	95% CI (Lower–Upper)
CADC-ELC vs CADC	14.07	0.85	<.0001	12.02 – 16.11
CADC-ELC vs Control	27.93	0.84	<.0001	25.92 – 29.95
CADC vs Control	13.87	0.87	<.0001	11.78 – 15.95

As shown in Table 4, all group differences were statistically significant, demonstrating the clear superiority of the CADC-ELC model over both the CADC-only and the conventional approaches. The Games–Howell analysis confirmed significant gaps: CADC-ELC vs. CADC (MD = 14.07, $p < .001$), CADC-ELC vs. Control (MD = 27.93, $p < .001$), and CADC vs. Control (MD = 13.87, $p < .001$). These large effect sizes indicate that the integrated CADC-ELC method produced the greatest improvement in students' written communication, particularly in expressing ideas clearly, organizing arguments, and using academically appropriate language. This enhanced performance may be attributed to the combination of structured peer comparison, iterative feedback cycles, and practitioner involvement, which provided students with authentic, context-rich writing experiences not available in the other instructional conditions.

Compared with recent studies reporting modest improvements in writing under collaborative or project-based models, the magnitude of improvement observed in the CADC-ELC group indicates a novel contribution: writing gains emerged from the combination of structured critique, comparison, and expert feedback, an approach not previously tested in high school Biology.

Table 5 displays the pre-test and post-test oral communication scores for each group.

Table 5. Oral Communication Skills – Pre-test and Post-test Averages

Group	Pre-test (0–100)	Category	Post-test (0–100)	Category
CADC-ELC	9.1	Poor	17.06	Excellent
CADC	8.1	Poor	13.00	Good
Control	7.3	Poor	9.06	Moderate

Table 6 presents the statistical comparison of group differences using the Games–Howell post hoc test.

Table 6. Games-Howell Post-Hoc Comparison – Oral Communication

Comparison	Mean Difference	Std. Error	Sig. (p)	95% CI (Lower–Upper)
CADC-ELC vs CADC	4.00	0.36	<.0001	3.11 – 4.89
CADC-ELC vs Control	8.00	0.32	<.0001	7.23 – 8.77
CADC vs Control	4.00	0.44	<.0001	2.93 – 5.07

As shown in Tables 5 and 6, oral communication performance, as assessed through classroom discussion observations, followed a similar pattern. At baseline, all groups were categorized as "poor": CADC-ELC (M = 9.1), CADC (M = 8.1), and Control (M = 7.3). Post-test results showed substantial gains for the CADC-ELC group, whose average rose to 17.06 ("excellent"), compared to 13.0 for the CADC group ("good") and 9.06 for the control group ("moderate"). Statistical analysis confirmed these differences were significant: CADC-ELC vs CADC (MD = 4.00, $p < .001$), CADC-ELC vs Control (MD = 8.00, $p < .001$), and CADC vs Control (MD = 4.00, $p < .001$).

These findings, as summarized in Tables 5 and 6, suggest that the CADC-ELC model, with its emphasis on structured group discussion, argumentation, and expert-led dialogue, effectively increased students' confidence, listening skills, and ability to formulate and express opinions. The comparative structure of the discussions, in which students actively engaged with others' ideas, promoted dialogic competence and verbal reasoning. Furthermore, the presence of external practitioners likely reinforced the relevance of spoken contributions, encouraging students to articulate their understanding more clearly and professionally.

These results indicate the novelty of CADC-ELC in promoting oral proficiency through structured rebuttal and expert-facilitated discussion methods, not commonly used in secondary science classrooms. Unlike previous findings reporting limited oral engagement in discussion-based learning, the integration of practitioner-led dialogue in CADC-ELC resulted in far higher verbal articulation and interaction competence.

Table 7 summarizes students' cognitive performance before and after the intervention in all three groups.

Table 7. Cognitive Abilities – Pre-test and Post-test Averages

Group	Pre-test (0–100)	Category	Post-test (0–100)	Category
CADC-ELC	33.3	Poor	83.1	Excellent
CADC	43.4	Poor	60.6	Good
Control	40.7	Poor	47.8	Moderate

The significance of these cognitive differences was tested using the Games–Howell procedure, as displayed in Table 8.

Table 8. Games-Howell Post-Hoc Comparison – Cognitive Abilities

Comparison	Mean Difference	Std. Error	Sig. (p)	95% CI (Lower–Upper)
CADC-ELC vs CADC	12.57	1.97	<.0001	7.79 – 17.35
CADC-ELC vs Control	35.32	1.46	<.0001	31.81 – 38.82
CADC vs Control	22.75	2.07	<.0001	17.76 – 27.74

As shown in Tables 7 and 8, cognitive performance, assessed using a 30-item multiple-choice test spanning six levels of Bloom's taxonomy, showed substantial gains in the experimental groups. At pre-test, all groups were in the "poor" range: CADC-ELC (M = 33.3), CADC (M = 43.4), and Control (M = 40.7). After the intervention, the CADC-ELC group's average rose to 83.1 ("excellent"), the CADC group to 60.6 ("good"), and the control group to 47.8 ("moderate"). Games-Howell comparisons showed significant differences across all groups:

CADC-ELC vs CADC (MD = 12.57, $p < .001$), CADC-ELC vs Control (MD = 35.32, $p < .001$), and CADC vs Control (MD = 22.75, $p < .001$). These results, as presented in Tables 7 and 8, confirm the CADC-ELC model's capacity to foster higher-order thinking and conceptual integration in Biology learning. The critical analysis tasks encouraged students to connect ideas, evaluate evidence, and reflect on ecological processes, while expert practitioner input contextualized theoretical concepts. The scaffolded discussion structure supported cognitive engagement through active dialogue, clarification of misunderstandings, and deeper conceptual processing.

Overall, across all three domains, encompassing written communication, oral communication, and cognitive achievement, the CADC-ELC method significantly outperformed both the CADC-only and conventional instruction models. The integration of critical analysis, peer comparison, and real-world engagement created a learning environment conducive to active thinking, expression, and deep understanding. The findings support the CADC-ELC model as a pedagogically sound and effective strategy for enhancing essential academic competencies in high school Biology education.

These results provide strong empirical evidence that the CADC-ELC model supports higher-order cognitive processing, addressing a major gap identified in the literature, that critical analysis models are rarely tested with secondary learners in conceptually demanding subjects like Biology. Compared with recent cognitive learning studies (Hidayati et al., 2023), which reported incremental but limited gains under inquiry- or PBL-based models, the magnitude of cognitive improvement in CADC-ELC demonstrates a distinct and novel instructional advantage.

This study examined the effectiveness of the Critical Analysis and Discussion Comparison with Extended Learning Community (CADC-ELC) method in enhancing secondary students' written and oral communication skills and cognitive performance in Biology. It responded to persistent global and national challenges in science education, where conventional didactic models have failed to cultivate core academic competencies, particularly in lower- and middle-income countries such as Indonesia (Hamzah et al., 2023; Marhama et al., 2017). Situated within a dialogic-constructivist theoretical framework, CADC-ELC integrates critical thinking, structured peer interaction, and practitioner engagement, elements strongly recommended by international pedagogical reforms but rarely implemented holistically at the high school level (Kilpatrick et al., 2012; Mercer & Howe, 2012). The model addresses major educational gaps by embedding scientific reasoning and communication in socially mediated, context-rich learning environments (Brown et al., 1989). Moreover, it advances scholarship in science pedagogy by providing empirical evidence for the application of university-level innovations, such as critical analysis (Susilo et al., 2018; Fitriani et al., 2024) and extended learning communities (Cassandra et al., 2024; Firdaus, 2018), in secondary classrooms, which remain understudied.

In relation to the first research objective, the findings revealed substantial improvements in students' written communication in the CADC-ELC group, significantly exceeding gains observed in the CADC-only and conventional instruction groups. These results confirm that traditional instructional methods, which prioritize content transmission over articulation and argumentation, are insufficient for developing scientific writing competencies. The CADC-ELC model's peer comparison stages and expert feedback cycles created meaningful, iterative writing opportunities in which students revised their analyses through critical dialogue, a condition often missing in standard classrooms (Nilam & Yenti, 2023). These improvements are not merely procedural; they signal cognitive advancement through written synthesis, coherence, and clarity. The structured format provided the metacognitive scaffolding needed to move beyond surface-level summaries toward deeper analytical writing, as advocated by social constructivist theorists (Vygotsky & Cole, 1978; Mercer & Howe, 2012). Furthermore, unlike studies where discussion alone yielded negligible gains in writing (Tan et al., 2020; Pradana et al., 2024), CADC-ELC's integration of authentic practitioner engagement lent relevance and urgency to student writing, motivating learners to align their expression with real-world discourse norms.

Regarding the second objective, the CADC-ELC group exhibited statistically significant improvements in oral communication compared to the other groups. This is a critical finding in contexts like Indonesia, where verbal participation in science classrooms is often minimal due to fear of error, passive learning habits, and rigid teacher control (Ningsih et al., 2017; Indriawati et al., 2018; Angganing et al., 2022). The CADC-ELC model operationalizes dialogic learning theory by facilitating structured, multi-stage classroom dialogues in which students formulate questions, respond to peer critiques, and articulate rebuttals, interactive mechanisms known to enhance verbal reasoning (Chen, 2019). Moreover, the presence of external practitioners raised the stakes of classroom discussions, encouraging students to use precise language and present their ideas confidently, mirroring professional communication contexts. These results differ sharply from previous studies, where generic discussion strategies or digital platforms often failed to generate meaningful oral interaction (Murphy et al., 2021; Orawiwatnakul & Wichadee, 2016). The improvement in oral expression within CADC-ELC demonstrates the necessity of intentional scaffolding, comparative structures, and contextual relevance in fostering dialogic competence.

The third objective, focused on cognitive learning outcomes, yielded equally compelling results. Students in the CADC-ELC group moved from "poor" to "excellent" performance on Bloom's taxonomy-aligned assessments, outperforming both the CADC-only and control groups by a wide margin. These gains underline the power of integrating critical thinking and social interaction in science instruction. While previous studies affirmed the value of critical analysis in promoting conceptual understanding at the university level (Irwandi & Hasan, 2021; Bilki & Irgin, 2022) this study demonstrates that similar gains are attainable in high school settings when instructional design is adapted to developmental needs. The real-world grounding of Biology content, facilitated through practitioner involvement, gave abstract ecological and conservation concepts tangible relevance, an application of situated cognition theory (Brown et al., 1989). Furthermore, the Zone of Proximal Development (ZPD) was activated through peer-led comparisons and mentor guidance, enabling students to internalize disciplinary thinking progressively. Compared to traditional content delivery, which often results in inert knowledge (Maridi et al., 2019; Yanti et al., 2024), the CADC-ELC model appears to cultivate deep learning that is both transferable and enduring.

Overall, these findings contribute to a growing body of literature calling for integrative, evidence-based instructional models in science education. Unlike conventional methods that isolate cognition, communication, or community engagement, the CADC-ELC model synthesizes these elements into a coherent pedagogical framework grounded in dialogic-constructivist theory. Its success in the secondary context contrasts with the limited efficacy of standalone methods such as group discussion (Cleopas & Igbojinwaekwu, 2023), unstructured learning communities (Lubis & Sulaiman, 2022), or digital-only interventions (Murphy et al., 2021; Pradana et al., 2024). It also addresses gender and engagement disparities noted in past discussion-based research (Jatau et al., 2021; Omovie & Kpangban, 2023), offering a more inclusive and participatory environment. By demonstrating that adolescent learners, often underestimated in terms of cognitive and communicative capacity, can excel when placed in well-structured, socially rich learning settings, this study opens new avenues for scalable pedagogical innovation. Future research should examine the longitudinal impacts of CADC-ELC, explore its adaptability across disciplines, and evaluate its effectiveness in diverse educational systems globally.

CONCLUSION

This study concludes that the CADC-ELC model, combining critical analysis, discussion comparison, and extended learning community engagement, significantly improves high school students' written communication, oral communication, and cognitive learning outcomes in Biology. These findings clearly meet the research objectives and demonstrate that CADC-ELC is more effective than both CADC-only and conventional instruction in strengthening key components of scientific literacy. Although the results are promising, the study was limited by its single-site context and short intervention period. The chosen school is an A-accredited school in which students have higher average abilities than those at other schools; therefore, it is believed to be able to represent other schools. Future research should examine longer implementations across varied school settings to validate the model's broader applicability. Overall, the study provides novel evidence that integrating critical analysis with practitioner-supported dialogue offers a practical, scalable approach to enhancing scientific literacy in secondary education.

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