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Grade 12 Students' Critical Thinking Competency in Learning Asexual Reproduction Through the CT-HOT in Bio Instructional Innovation

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Abstract

This study reports the third phase (R3) of an iterative six-phase Research and Development (R–D–R–D–R–D) project designed to cultivate secondary students' critical thinking through the CT-HOT in Bio instructional innovation. Grounded in constructivist theory, the 7Es inquiry model, and the P–I–A–C framework (Problem Posing, Information Seeking, Analyzing Data, Concluding/Evaluating), this study examined the effects of the systematically refined innovation on Grade 12 students' critical thinking during an asexual reproduction unit. The participants comprised 39 Grade 12 students enrolled in a biology course during the 2025 academic year at Kanlayanawat School, Thailand. A mixed-methods design was utilized: quantitative critical thinking scores were evaluated using an analytic rubric across the four P–I–A–C dimensions, while qualitative cognitive artifacts and reflective records were examined via content analysis. Findings revealed that 84.62% of students (n = 33) achieved an "Excellent" competency level, with 53.85% (n = 21). Furthermore, 10.26% (n = 4) performed at the "Good" level and 5.13% (n = 2) at the "Fair" level; no students were classified under "Needs Improvement." Qualitative analysis of dimensional profiles revealed that learners exhibited differentiated cognitive trajectories, with some excelling in early problem-framing but encountering constraints in data analysis or source triangulation. Overall, the refined CT-HOT in Bio innovation effectively promoted critical inquiry and evidence-based reasoning in biology, providing foundational empirical evidence for developing the Phase D3 instructional manual and advancing competency-based secondary science pedagogy.

Keywords: Critical Thinking Competency, Asexual reproduction, Biology, Instructional innovation

1. Introduction

Contemporary biology education at the secondary level increasingly demands more than the rote memorization of biological facts and processes; it requires the cultivation of learners' capacities to connect scientific content with social, ethical, and real-world decision-making contexts. Busch et al. (2026) have persuasively argued that the world is confronting increasingly complex challenges, such as pandemics, climate change, and advances in genetic technology. They assert that these challenges necessitate solutions grounded simultaneously in scientific discovery and humanistic understanding. Science

education, therefore, cannot be effectively delivered in isolation from its societal context (American Association for the Advancement of Science, 2011). STEM classrooms, in particular, represent critical spaces in which students can identify, analyze, and grapple with authentic real-world problems situated at the intersection of science and society.

Educators often integrate social and cultural issues into biology instruction and assessment, an approach known as embedding content within a social context. This practice has demonstrated considerable potential to enhance student engagement, foster a sense of belonging, strengthen academic commitment, and help students view biology as a vehicle for social transformation (Thoman et al., 2025; Busch et al., 2026). Furthermore, empirical evidence suggests that students' critical engagement with the interconnections between science and society is positively associated with gains in content knowledge (Sadler et al., 2016; Young et al., 2023). These findings collectively underscore those biology curricula that merely transmit disciplinary content, without cultivating higher-order thinking skills and socially situated reasoning, may be insufficient to prepare students for the complexities of contemporary life.

At the international level, comparative curriculum research reinforces this imperative. Lin et al. (2023), through a comprehensive review of national biology curricula across multiple countries, identified three core competencies that biology education should systematically cultivate: Action, Literacy, and Problem-solving. These competencies were found to be broadly applicable across diverse biological content areas, suggesting that the development of student competencies in biology learning has become a widely endorsed educational goal on the global stage (Bauphitak et.al., 2024; Wongsila & Yuenyong, 2019). This international consensus aligns closely with Thailand's competency-based curriculum reform, which similarly emphasizes the cultivation of higher-order thinking skills, with critical thinking positioned as a central competency to be developed within the context of biology education.

The design of instructional innovations intended to cultivate critical thinking competencies must be firmly grounded in learning theory. Constructivism, rooted in the seminal work of John Dewey, Jean Piaget, and Lev Vygotsky (Davis & Sumara, 2002), provides such a foundation. Its central tenet holds that learning is an internally constructed process, wherein learners actively build knowledge by connecting new information and experiences to their pre-existing cognitive structures (Merriam, Caffarella, & Baumgartner, 2007). Glasersfeld (1989) further elaborated that constructivism constitutes an epistemological theory rooted in philosophy, psychology, and communication studies, positing that knowledge is not passively received but actively constructed by the knowing subject. Fosnot (1993) extended this understanding, characterizing knowledge as provisional, developmental, and socioculturally mediated, with learning conceived as a self-regulated process arising from the resolution of conflict between existing and newly encountered knowledge.

Constructivist theory bifurcates into two complementary strands: cognitive constructivism, associated with Piaget, and social constructivism, associated with Vygotsky. Piaget's cognitive constructivism emphasizes that learners construct knowledge through direct action upon their environment; when learners encounter situations that generate cognitive conflict or disequilibrium, they strive to restore cognitive equilibrium through the complementary processes of assimilation (incorporating new information into existing cognitive structures) and accommodation (modifying existing structures to accommodate new information). Of particular relevance to the present study is Piaget's Formal Operations Stage (from approximately age 12 onward), during which learners develop the capacity for hypothetical-deductive reasoning, scientific thinking, hypothesis generation, theory construction, and abstract reasoning—cognitive capacities that align directly with the developmental requirements for critical thinking competency among Grade 12 students.

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Complementing this, Vygotsky's social constructivism emphasizes the pivotal role of social interaction in cognitive development (Vygotsky, 1978, 1986). Central to this framework is the concept of the Zone of Proximal Development (ZPD)—the gap between what learners can accomplish independently and what they can achieve with guided assistance from teachers or peers, commonly operationalized through scaffolding (Chaiklin, 2003; van de Pol et.al., 2010). This concept directly informs the design of Scaffolding Questions, a core structural component of the CT-HOT in Bio innovation developed in this study.

The instructional design process grounded in constructivist theory typically commences with complex problems that generate cognitive conflict, prompting learners to draw upon prior knowledge and experience to assimilate or accommodate new understanding. Teachers assume the role of facilitators who construct conditions conducive to disequilibrium, stimulate learner-driven knowledge construction, and orchestrate activities involving debate, argumentation, and evidence-based reasoning to resolve cognitive conflict. This theoretical orientation constitutes the foundational architecture of the CT-HOT in Bio instructional model, which is designed to guide students through inquiry-based knowledge construction, Analyzing data, and evidence-based conclusion-drawing within authentic biological content.

Rapid technological advancement and the transition toward a digital society have precipitated significant social, cultural, and economic transformation, necessitating corresponding reforms in educational processes to cultivate learners equipped with the capacities and dispositions required for effective participation and competitive collaboration in the global arena (Institute for the Promotion of Teaching Science and Technology, 2021). Competency-based instruction, as articulated by the Office of the Education Council (2020), is fundamentally oriented toward learner outcomes—specifically, the holistic application of knowledge, skills, and attitudes in problem-solving, task performance, and real-life engagement. Such instruction emphasizes active learning approaches that equip learners with the capacities to navigate contemporary societal change, resolve everyday problems, and function as informed, engaged citizens (Office of the Basic Education Commission, 2022).

Within this competency-based paradigm, inquiry-based instruction serves as a critical pedagogical vehicle. Inquiry-based learning, as conceptualized by Khaemmanee (2007), involves instructional processes wherein teachers stimulate learner curiosity, provoke critical questioning, and guide students toward independent knowledge-seeking to derive conclusions. Eisenkraft (2003) extended the traditional 5E instructional cycle into a more elaborated seven-stage model known as the 7Es. This model comprises Elicitation, Engagement, Exploration, Explanation, Elaboration/Expansion, Evaluation, and Extension, and is designed to promote learner autonomy, direct experiential engagement, and the practical application of knowledge. This 7Es framework constitutes the structural backbone of the CT-HOT in Bio model, integrated systematically with a critical thinking competency development framework to create a coherent, biology-contextualized learning process that promotes higher-order thinking in a systematic and scaffolded manner.

Scholarly conceptualizations of critical thinking have varied considerably, yet converge on several core dimensions. Watson and Glaser (1980) identified three foundational components: attitude (a disposition toward inquiry), knowledge (the capacity for reasoned evidence-seeking), and skill (the application of attitude and knowledge). Within this framework, they further specified five measurable sub-competencies: inference, recognition of assumptions, deduction, interpretation, and evaluation of arguments. Paul (1993) proposed a seven-element framework encompassing purpose, question at issue, information, empirical grounding, reasoning, assumptions, and implications/consequences. Building upon these international frameworks, Nekmanurak (1994) synthesized a seven-dimensional framework for the Thai educational context. It

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includes problem identification, information gathering, assessment of information credibility, characterization of data, hypothesis formulation, conclusion-drawing, and evaluation of conclusions. The present researcher considers this framework to be particularly comprehensive and pedagogically actionable.

The significance of critical thinking as a twenty-first-century competency is well-documented. Bassham et al. (2011) delineate its importance across three domains: academically, it enhances comprehension of arguments and complex issues; professionally, it accelerates learning, problem-solving, and clear communication; and in daily life, it safeguards against faulty decision-making, strengthens democratic society, and reduces bias. The Office of the National Education Commission (1997) similarly emphasizes that critical thinking enables learners to work systematically, evaluate outcomes against reasoned criteria, practice problem-solving, think with clarity and depth, and cultivate lifelong learning capacities. Khaemmanee (2008) further notes that critical thinking supports goal-setting, empirical data collection, hypothesis formulation, interpretation, and conclusion-drawing—processes fundamental to lifelong learning. As Panich (2012) poignantly observes, genuine critical thinking proficiency must be cultivated not merely within instructional periods but through continuous teacher-student interaction embedded in daily practice until it becomes habitual disposition.

Thailand's Competency-Based Education (CBE Thailand) framework (Office of the Education Council, 2021), aligned with the Basic Education Core Curriculum B.E. 2551, situates critical thinking within Core Competency 2 (Thinking Ability), specifying that Grade 10–12 students should attain Level 9 proficiency, characterized by the ability to summarize understanding, articulate reasoned opinions and counterarguments, analyze and evaluate the adequacy of information, draw accurate conclusions or make decisions, cite multiple sources of supporting evidence, and justify decisions while considering multifaceted advantages and disadvantages.

Synthesizing this national framework with international scholarly literature, the present study operationalizes critical thinking competency through four integrated components, referred to as P-I-A-C. These components comprise: (1) Problem Identification (P), which involves recognizing and framing problems based on evidence and argumentation; (2) Investigation (I), planning and conducting systematic inquiry while evaluating the credibility and sufficiency of information; (3) Analysis (A), comparing data sources and evidence to identify the most reasonable alternatives; and (4) Conclusion and Evaluation (C), drawing conclusions and assessing their robustness under changing conditions or additional information. This P-I-A-C framework directly informs the design of both the rubric-based assessment criteria (four-level scale: excellent, good, fair, and needs improvement) and the Scaffolding Questions embedded within the CT-HOT in Bio innovation.

Empirical precedents substantiate the feasibility and effectiveness of instructional designs targeting critical thinking within biology education. Several studies have explicitly targeted critical thinking as a primary outcome variable, employing structured rubrics and staged cognitive frameworks to both scaffold and assess this competency. Bauphitak et al. (2024) developed a Grade 11 instructional unit on flowering plant reproduction designed around twenty-first-century critical thinking skills. The curriculum embedded reproductive biology content within a Science, Technology, and Society (STS) framework by linking plant propagation to real-world agricultural and horticultural applications. This approach systematically developed students' capacities to identify problems, evaluate evidence, and draw justified conclusions. Similarly, Wongsila and Yuenyong (2019) targeted both critical thinking and problem-solving ability among Grade 12 students within a genetics and DNA technology unit, a content area inherently laden with ethical and societal dimensions (e.g., genetic testing, biotechnology applications) that necessitate evaluative reasoning beyond factual comprehension. Both studies suggest that critical

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thinking is most effectively promoted when instructional design explicitly incorporates structured decision-making tasks, rather than treating it as an incidental byproduct of content mastery. These tasks require students to actively weigh scientific evidence against social, ethical, and practical considerations. Across the reviewed studies, STS-based instruction has been applied to an unusually broad range of scientific content areas, spanning both physical and biological sciences, which underscores the approach's adaptability. In the physical sciences, STS units have been developed for sound (Chantaranima & Yuenyong, 2014), electricity and electric power (Suparee & Yuenyong, 2021a, 2021b), circular motion (Seattha et.al., 2015; Seattha et.al., 2016), electromagnetics (Yuenyong, 2012), fluid mechanics (Nongkhunsarn et.al., 2019), electric fields (Chitnork & Yuenyong, 2019), wave motion integrated with STEM (Tupsai et.al., 2019), force and motion (Jimakorn & Yuenyong, 2018), and light/optics through the contact lens unit (Attapan & Yuenyong, 2019). In the life sciences, STS units have addressed genetics and DNA technology (Wongsila & Yuenyong, 2019) and plant reproduction (Bauphitak et.al., 2024), while socio-scientific and environmental issues such as global warming (Luengam et.al., 2019) have also been incorporated.

Despite this accumulating evidence base, limited attention has been paid to the specific content domain of asexual reproduction, a topic requiring students to reason critically about biological mechanisms with significant applications in agriculture, biotechnology, and conservation—contexts rich in social relevance yet underexplored in critical thinking intervention research. Moreover, few studies have integrated constructivist-grounded 7Es inquiry structures with a locally validated, competency-based (CBE Thailand) assessment framework in an iterative, evidence-refined instructional design process.

To address this gap, the present study constitutes the third research phase (R3) within a broader Research and Development (R&D) initiative employing an iterative R–D–R–D–R–D cyclical design. This overarching design progresses through six interconnected phases spanning research (R) and development (D). The sequence begins with framework and innovation development (R1, D1), continues through two implementation and refinement cycles (R2 in 2024, D2, and R3 in 2025), and concludes with the creation of an implementation manual (D3). Throughout this structure, each developmental phase is informed by preceding empirical findings, while each research phase generates evidence for subsequent refinement.

This paper specifically reports the R3 phase, addressing the following research question: What are the effects of the revised CT-HOT in Bio instructional innovation on the critical thinking competency of Grade 12 students during the second implementation phase in the 2025 academic year, within the content area of asexual reproduction? By integrating constructivist theory, the 7Es inquiry model, and the P-I-A-C competency framework, this study aims to generate robust empirical evidence regarding the efficacy of a systematically refined, theoretically grounded instructional innovation, thereby contributing both to the localized advancement of competency-based biology education in Thailand and to the broader international discourse on cultivating critical thinking within secondary science education.

2. Methodology

The present study constitutes the R3 phase of an overarching Research and Development (R&D) initiative. The overall research design followed an iterative R–D–R–D–R–D cyclical architecture, progressing sequentially through six phases that alternated between empirical research inquiry and instructional innovation development. This structure reflects the iterative and continuous nature of educational R&D, wherein each development phase is informed by the findings of the preceding research phase, and each

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subsequent research phase evaluates the empirical outcomes of the implemented innovation to establish an evidence base for further refinement.

These six phases align directly with the six sub-research questions (R1, D1, R2, D2, R3, D3) and collectively address the main research question regarding the development and evaluation of an instructional model designed to foster Grade 12 students' critical thinking competencies in biology. The six phases are structured as follows:

- R1: Theoretical development of the CT-HOT in Bio instructional framework.
- D1: Development of the initial version of the CT-HOT in Bio instructional innovation.
- R2: Phase 1 implementation and evaluation of the initial CT-HOT in Bio instructional innovation (Academic Year 2024).
- D2: Systematic refinement of the CT-HOT in Bio instructional innovation into a revised edition.
- R3: Phase 2 implementation and evaluation of the revised CT-HOT in Bio instructional innovation (Academic Year 2025).
- D3: Development of the CT-HOT in Bio Instructional Implementation Manual for Biology Teachers.

This paper specifically reports on the R3 phase: Implementation and Evaluation Phase 2 (Academic Year 2025), addressing the following research question:

What are the effects of the revised CT-HOT in Bio instructional innovation on the critical thinking competency of Grade 12 students during the second implementation phase in the 2025 academic year?

2.1 Participants

The participants in this implementation and evaluation phase (R3) comprised 39 Grade 12 students enrolled in a biology course during the first semester of the 2025 academic year at Kanlayanawat School.

The participants were instructed using the revised CT-HOT in Bio instructional innovation to examine its effects on their critical thinking competency, analyze their thinking traces (cognitive artifacts), evaluate performance outcomes, and identify emerging strengths, limitations, and contextual implementation factors. The empirical data derived from this phase (R3) served as the evidence base for synthesizing findings, practical guidelines, and pedagogical caveats necessary for constructing the comprehensive teacher instructional manual in the subsequent final phase (D3).

2.2 Intervention: The CT-HOT in Bio Instructional Innovation on Asexual Reproduction

The instructional innovation on "Asexual Reproduction" was developed based on the Critical Thinking and Higher-Order Thinking in Biology (CT-HOT in Bio) instructional model, which was established during Phase D1. The CT-HOT in Bio instructional framework comprises four core components:

(a) Theoretical Rationale: The CT-HOT in Bio model is grounded in the integration of constructivist learning theory and competency-based education. It is based on the premise that students develop critical thinking competencies most effectively when confronted with biological problems situated in real-world or socioscientific contexts, supported by systematic and progressively faded cognitive scaffolding questions.

(b) Instructional Process (Integration of 7E and PIAC): The instructional process integrates the 7-stage inquiry-based learning model (7E) with the 4-step critical thinking process (PIAC), as outlined in Table 1.

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Table 1 Alignment between the 7E Inquiry Steps and the PIAC Critical Thinking Stages in the CT-HOT in Bio Model

7E Stage	Instructional Objective	Linked PIAC Thinking Stage
1. Elicitation	Assess students' prior foundational knowledge	Preparation prior to Step P
2. Engagement	Present problem situations that trigger cognitive conflict	P – Identify Problem (Goal setting & problem identification)
3. Exploration	Plan and conduct investigations using multiple information sources	I – Investigate (Planning & conducting investigation)
4. Explanation	Analyze data, engage in scientific discussion, and present findings	A – Analyze Data
5. Elaboration	Transfer and apply knowledge to more complex, novel contexts	Bridge from Step A to Step C
6. Evaluation	Assess learning outcomes using diverse evaluation tools	Holistic assessment across all P–I–A–C stages
7. Extension	Make reasoned, evidence-based decisions for real-world application	C – Conclude and Evaluate

(c) Teacher and Student Roles across Instructional Stages: The framework defines the teacher's role as a problem designer, a provider of gradual cognitive scaffolding, and a learning facilitator. Conversely, students actively engage as self-directed learners who investigate, analyze, and make decisions independently. Consistent with Vygotsky's Zone of Proximal Development (ZPD), instructional guidance is progressively faded as students demonstrate greater cognitive autonomy.

(d) PIAC-Based Student Assessment Framework: The model assesses critical thinking competency using a four-dimensional rubric aligned with the PIAC stages across four performance levels (Exemplary, Good, Fair, and Developing/Needs Improvement). This is coupled with a multi-source assessment approach—incorporating teacher evaluation, student self-assessment, and peer assessment—to provide comprehensive data reflecting genuine student development.

The instructional innovation on "Asexual Reproduction" represents one of the 11 instructional units in the revised (2025) CT-HOT in Bio curriculum package. The complete instructional package features refined learning activities, assessment rubrics, and cognitive scaffolding question sets distributed across 11 lesson plans. These included 1) Asexual Reproduction (2 hours), 2) Animal Reproduction: Sexual Reproduction (2 hours), 3) Human Reproduction: Male Reproductive System (2 hours), 4) Human Reproduction: Female Reproductive System (2 hours), 5) Female Reproductive System: Hormones and the Reproductive Cycle (2 hours), 6) Structures of Animal Reproductive Organs (1 hour), 7) Fertilization and Pregnancy (2 hours), 8) Animal Development: Frog (2 hours), 9) Animal Development: Chicken (2 hours), 10) Human Development (2 hours), 11) Growth Rates in Animals (2 hours)

This research paper specifically reports on the critical thinking competency of Grade 12 students who participated in the "Asexual Reproduction" unit, which is one of the eleven designated lesson plans. Lesson Plan on Asexual Reproduction Based on the Revised CT-HOT in Bio Model will be clarified into three sections. These included 1) key features of the revised learning activities, 2) revised assessment criteria, and 3) revised scaffolding questions

1) Key Features of the Revised Learning Activities

The lesson plan on Asexual Reproduction (2 hours) was restructured to enhance the systematic organization of learning activities. The plan retained the integration of the 7E Inquiry-Based Learning Cycle with the four-step Critical Thinking Process (P-I-A-C:

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Problem identification, Investigation, Analysis, and Conclusion) as its core framework. However, the Problem Identification (P) stage was strengthened by requiring students to consult at least two credible sources before finalizing their group's problem statement. This modification directly addressed a limitation identified during the R2 phase, wherein students tended to formulate problem statements based on prior knowledge or personal experience without evidence-based justification.

The use of the real-world context of the New Guinea flatworm invasion as a stimulus for critical thinking was retained as a key strength of the lesson. Additional refinements included clearly defined role assignments within groups and the incorporation of a cross-verification activity for assessing the consistency and credibility of information obtained during the Exploration stage, which was linked to the Investigation (I) stage. This modification aimed to systematically strengthen students' information literacy skills.

The Analysis (A) stage, identified as the area with the most significant limitations during R2, was enhanced through the addition of an Elaboration phase. Students were required to analyze and compare at least two population-control approaches using a structured table comprising "Control Method – Scientific Principle – Advantages – Disadvantages." This modification elevated the depth of analysis from a superficial level to an evidence-based comparative analysis. In the Conclusion (C) stage, a real-world application component was added, requiring students to develop policy recommendations for invasive species management within their community. This was designed to promote decision-making grounded in scientific evidence rather than personal opinion.

Furthermore, an individualized learning support system called the 'Critical Thinking Clinic' was introduced via the Canva platform. This system was designed specifically for students whose performance fell below the 'Good' level. This clinic provided targeted remedial practice specifically for underdeveloped stages of the thinking process, consistent with Vygotsky's Scaffolding principle within the Zone of Proximal Development (ZPD).

2) Revised Assessment Criteria

The assessment criteria embedded in the lesson plan were refined to be more specific to each stage of the P-I-A-C process, with a minimum passing threshold set at the "Good" level (Level 3) for all stages. Discipline-specific criteria reflecting the nature of biological science were incorporated, including: the use of at least two credible sources during the P and I stages, scientifically reasoned comparison of alternatives during the C stage, and evaluation of the contextual appropriateness of proposed solutions. Additionally, the assessment framework was linked to more diverse and concrete evidence of learning, including: the four-part Critical Thinking Activity Record (P-I-A-C), scores from online Live Worksheets activities (with a minimum passing score of 7 points), Self-Assessment Rating Scales, and Peer Assessment forms. These enabled students to reflect on their own learning processes and receive feedback from multiple perspectives. Collectively, these components enhanced the clarity, comprehensiveness (encompassing both teacher and student perspectives), and systematic measurement of student development compared to the original version.

3) Revised Scaffolding Questions

The scaffolding questions were designed as a hierarchical ladder of cognitive support aligned with each stage of the thinking process. In the P stage, questions activated prior knowledge (e.g., "Why can asexual reproduction enable certain organisms to multiply rapidly?") and confirmed problem framing (e.g., "How can the reproduction of this species be controlled without harming other aspects of the environment?"). In the I stage, questions probed the credibility of information (e.g., "What similarities or differences exist between the two data sources, and why?"). In the A stage, mechanistic questions linked

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reproductive characteristics to systemic impacts (e.g., "How does this species' mode of asexual reproduction facilitate its rapid spread?"). In the C stage, questions prompted comprehensive evaluation of alternatives (e.g., "Can the chosen method be combined with other approaches? How?"). These questions were designed to allow teachers to adjust the level of support according to individual student competency, without providing answers directly—an improvement that directly addressed the individualized support limitations identified during R2.

2.3 Research Instruments

The R3 phase employed the following instruments to examine the effects of the revised CT-HOT in Bio learning innovation on students' critical thinking competency:

1. Critical Thinking Competency Rubric (P-I-A-C)

The P-I-A-C rubric served as a component of the CT-HOT in Bio innovation, used to assess evidence of student thinking and performance across the P-I-A-C process. It was developed based on the behavioral indicators of CBE Thailand Competency Level 9 for upper secondary students.

The rubric was structured as an analytic rubric comprising four dimensions: Problem Identification (P), Investigation Planning and Implementation (I), Analyzing data (A), and Conclusion and Evaluation (C). Each dimension was rated on a 4-point quality scale (1–4), yielding a total score range of 4–16 points. During the R2 implementation and evaluation phase, the researcher retained the original structure, behavioral indicators, and quality levels to ensure consistency of assessment standards across both phases, while refining the activity record forms, question sequencing, and wording to elicit clearer evidence of student thinking aligned with each rubric dimension.

2. Revised Scaffolding Questions for Critical Thinking

The scaffolding questions constituted the third component of the revised CT-HOT in Bio innovation, designed to support students' thinking processes through the P-I-A-C stages. Questions were sequenced from establishing problem focus and checking comprehension, to utilizing data and evidence, providing scientific reasoning, analyzing biological mechanisms, evaluating the credibility and sufficiency of information, and finally considering alternatives prior to drawing conclusions or making decisions.

Teachers adjusted the level of questioning to match individual student needs and competency levels. Through this approach, they provided targeted support that decreased as students demonstrated greater independent thinking. This practice aligns directly with the Zone of Proximal Development (ZPD) and scaffolding principles.

3. Situational Critical Thinking Assessment

This instrument was used to collect data on students' critical thinking competency through biology-related scenarios connected to the unit on reproductive systems and growth. Open-ended questions allowed students to demonstrate their thinking process across the P-I-A-C stages: Problem Identification (P), Investigation Planning and Implementation (I), Analyzing data (A), and Conclusion and Evaluation (C).

4. Researcher's Field Notes

Field notes were used to record events and observations during the implementation of the revised CT-HOT in Bio innovation, covering student responses to activities, evidence of thinking according to the P-I-A-C process, learning engagement, responses to scaffolding questions, as well as problems, limitations, and classroom conditions. This descriptive data was used in conjunction with evidence from competency assessments, activity records, student work, and other relevant sources to interpret the results.

5. Critical Thinking Development Activity Record (P-I-A-C)

This instrument was used to structure activities and record evidence of student thinking according to the P-I-A-C process within each lesson plan. Scenarios and tasks

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were designed to align with the content and learning objectives of each plan. These tasks enabled students to demonstrate sequential thinking processes, from Problem Identification (P) and Investigation Planning and Implementation (I), to Analyzing data (A) and Conclusion and Evaluation (C). Throughout this process, students used data, evidence, and biological principles to support their reasoning and decision-making.

Student responses and work recorded in these activity sheets served as evidence of thinking, which was assessed using the P-I-A-C rubric to determine quality in each dimension and overall competency level.

6. Online LiveWorksheets

Online LiveWorksheets served as supplementary learning media and tools for each lesson plan, designed to align with the content, scenarios, and learning objectives, enabling students to review, check their understanding, and apply relevant biological knowledge. To evaluate student understanding and learning outcomes, researchers used results from these worksheets as supporting evidence. This data was considered in combination with critical thinking activity records, situational assessments, and other learning outputs.

7. Researcher-Teacher's Reflective Journal

The reflective journal was maintained by the researcher, in the capacity of the classroom teacher, following each learning activity session to document activity outcomes, student responses, observed evidence of thinking, strengths, limitations, problems, and conditions arising from the implementation of the revised CT-HOT in Bio innovation. This data was used, together with evidence from other sources, to interpret the results of the R3 phase and to synthesize practical guidelines, conditions, and precautions for developing the CT-HOT in Bio teacher's manual in the subsequent D3 phase.

2.4 Data Analysis

Data collected during the R3 phase were analyzed in two categories: 1) primary data addressing the research question concerning the effects on students' critical thinking competency, and 2) supplementary data explaining opinions, experiences, strengths, limitations, and conditions related to the use of the revised innovation.

Quantitative data on critical thinking competency were analyzed using descriptive statistics, including frequency, percentage, and distribution of students' overall competency levels. Scores across the P-I-A-C dimensions were also examined to characterize performance patterns in each dimension, based on the Critical Thinking Competency Rubric (P-I-A-C).

Qualitative data derived from activity records, student work and thinking evidence, field notes, and the researcher's reflective journal were analyzed using Content Analysis, categorized according to the P-I-A-C process. This analysis examined students' use of data and evidence, connections to biological principles or mechanisms, reasoning, and the quality of their conclusions or evaluations.

Table 2: Rubric for Assessing Critical Thinking Competency in the Lesson Plan on Asexual Reproduction

Critical Thinking Stage	Excellent (4)	Good (3)	Fair (2)	Needs Improvement (1)
1. Problem Identification	Identifies the problem or issue from the given scenario based on the principle of asexual reproduction in invasive alien species affecting local ecosystems,	Identifies the problem or issue from the given scenario based on the principle of asexual reproduction in invasive alien species affecting local ecosystems,	Identifies the problem or issue from the given scenario based on the principle of asexual reproduction in invasive alien species affecting local ecosystems,	Unable to identify the problem or issue from the given scenario based on the principle of asexual reproduction in invasive alien

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	logically and precisely, using information from multiple sources	logically and precisely	but lacks logical consistency	species affecting local ecosystems
2. Investigation Planning and Implementation	Plans and conducts an appropriate investigation of asexual reproduction in invasive alien species, selecting suitable tools or technology to obtain supporting information from at least 2 comprehensive sources	Plans and conducts an appropriate investigation of asexual reproduction in invasive alien species, selecting suitable tools or technology to obtain supporting information from at least 2 sources, but lacking comprehensiveness	Plans and conducts an investigation of asexual reproduction in invasive alien species, selecting suitable tools or technology to obtain supporting information from only 1 source	Unable to plan and conduct an appropriate investigation of asexual reproduction in invasive alien species
3. Analyzing data	Uses evidence on asexual reproduction to propose population control methods for invasive alien species to maintain local ecosystem balance, grounded in scientific principles, while evaluating the appropriateness and sufficiency of the data	Uses evidence on asexual reproduction to propose population control methods for invasive alien species to maintain local ecosystem balance, grounded in scientific principles	Uses evidence on asexual reproduction to propose population control methods for invasive alien species to maintain local ecosystem balance, but without grounding in scientific principles	Unable to use evidence on asexual reproduction to propose population control methods for invasive alien species to maintain local ecosystem balance
4. Conclusion and Evaluation	Provides reasoned justification for the selected method of controlling asexual reproduction in invasive alien species to maintain local ecosystem balance, based on given data, with comprehensive and accurate consideration of advantages and disadvantages consistent with real-world ecological contexts	Provides reasoned justification for the selected control method based on given data, with comprehensive and accurate consideration of advantages and disadvantages, but not fully consistent with real-world ecological contexts	Provides reasoned justification for the selected control method based on given data, with accurate but incomplete consideration of advantages and disadvantages, inconsistent with real-world ecological contexts	Unable to provide reasoned justification for the selected method of controlling asexual reproduction in invasive alien species to maintain local ecosystem balance

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Table 3: Criteria for Determining Overall Quality Level Based on the P-I-A-C Framework

Total Score	Quality Level	Description
13–16 points	Level 4 (Excellent)	Students demonstrate a high level of critical thinking competency, able to conduct the thinking process comprehensively across all dimensions with quality, integrating biological knowledge, evidence, and reasoning in a thorough manner consistent with real-life contexts
9–12 points	Level 3 (Good)	Students demonstrate a satisfactory level of critical thinking competency, able to conduct the thinking process accurately in most dimensions, though some dimensions may lack depth or comprehensiveness
5–8 points	Level 2 (Fair)	Students demonstrate a basic level of critical thinking competency, able to conduct the thinking process partially, but with deficiencies in several dimensions requiring further development
4 points	Level 1 (Needs Improvement)	Students do not yet demonstrate an acceptable level of critical thinking competency and require urgent support and development across all dimensions of the thinking process

3. Research findings

The findings revealed students' critical thinking competency on the topic of asexual reproduction through the CT-HOT in Bio instructional innovation. The results are presented in two sections: 1) an overview of the levels of critical thinking competency on asexual reproduction, and 2) a highlighted account of the assessment of students' critical thinking competency levels on asexual reproduction.

3.1 Overview of the levels of critical thinking competency on asexual reproduction

Table 4 Results of Critical Thinking Competency Levels on Asexual Reproduction

Competency Level	P	I	A	C	Total score	Frequency	%
Excellent (13–16 points)	4	4	4	4	16	21	53.85
	3	4	4	4	15	3	7.69
	4	4	3	4	15	1	2.56
	4	3	4	4	15	1	2.56
	4	3	4	3	14	2	5.13
	3	3	4	4	14	1	2.56
	4	4	3	3	14	1	2.56
	3	4	3	4	14	1	2.56
	3	4	4	3	14	1	2.56
	3	4	3	3	13	1	2.56
Good (9–12 points)	4	4	1	3	12	1	2.56
	3	2	3	3	11	1	2.56
	4	1	1	4	10	1	2.56
	4	3	2	1	10	1	2.56
Fair (5–8 points)	2	2	2	2	8	1	2.56
	4	1	1	1	7	1	2.56
Needs Improvement (≤4 points)	–	–	–	–	–	0	0.00

The researcher assessed the critical thinking competency of 39 students following the implementation of Learning Activity Plan 21.1 on the topic of Asexual Reproduction. The assessment was based on students' thinking traces, responses, and written work, evaluated according to the analytic scoring rubric for critical thinking competency based on the P–I–A–C process. This rubric assesses thinking quality across four dimensions corresponding to the four stages of the P–I–A–C process: Setting Goals/Identifying the

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Problem or Issue for Thinking (P), Planning and Conducting Investigation (I), Analyzing Data (A), and Concluding and Evaluating (C). The results, classified by competency level and dimensional score patterns, are presented in Table 4.

(1) Excellent Level

A total of 33 students, or 84.62%, achieved the Excellent level. Among these, 21 students, or 53.85% of the total sample, obtained the full score of 4 points across all four dimensions, corresponding to a P–I–A–C score pattern of 4–4–4–4, totaling 16 points. The remaining 12 students obtained total scores ranging from 13 to 15 points, with varying dimensional score patterns. These results indicate that students whose overall competency level was classified as Excellent may nonetheless exhibit differing qualities of thinking across individual dimensions, as some students received only 3 points in the P, I, A, or C dimension. This suggests that the dimensional score pattern should be considered alongside the total score in order to accurately characterize the quality of each student's thinking process.

(2) Good Level

A total of 4 students, or 10.26%, achieved the good level, exhibiting four distinct P–I–A–C score patterns: 4–4–1–3, 3–2–3–3, 4–1–1–4, and 4–3–2–1, with one student corresponding to each pattern. These score patterns reflect that each student possessed distinct strengths and limitations across the four dimensions. Some students were able to clearly carry out the thinking process at the Problem Identification (P) stage but exhibited limitations at the Investigation (I) or Analysis (A) stages, whereas others performed well at the Concluding and Evaluating (C) stage despite incomplete use of data and evidence in the preceding stages.

(3) Fair Level

A total of 2 students, or 5.13%, achieved the Fair level. One student exhibited a P–I–A–C score pattern of 2–2–2–2, totaling 8 points, indicating the ability to carry out all four stages of the thinking process at a basic level, albeit lacking clarity and comprehensiveness. The other student exhibited a P–I–A–C score pattern of 4–1–1–1, totaling 7 points, indicating a clear ability to carry out the Problem Identification (P) stage but notable limitations at the Investigation (I), Analysis (A), and Concluding and Evaluating (C) stages. Both students would therefore benefit from additional practice and targeted support corresponding to the specific limitations identified at each stage of the thinking process.

(4) Needs Improvement Level

No students obtained a total score corresponding to the Needs Improvement level (0.00%), indicating that all students achieved an overall critical thinking competency assessment of at least the Fair level.

In summary, a total of 37 students, or 94.87%, achieved an overall critical thinking competency assessment of good level or above, comprising 33 students at the Excellent level and 4 students at the good level. The remaining 2 students achieved an overall assessment at the Fair level. Although the overall assessment results for the majority of students were at a high level, the P–I–A–C dimensional score patterns revealed notable individual variation in thinking quality, particularly with respect to limitations at the Investigation (I), Analysis (A), and Concluding and Evaluating (C) stages. Consequently, consideration of the total score alone is insufficient for a complete understanding of students' critical thinking competency. The researcher therefore incorporated the dimensional score patterns together with students' thinking traces, responses, and written work to support the in-depth interpretation presented in Section 3.2.

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3.2 Highlighted account of the assessment of students' critical thinking competency levels on asexual reproduction

Based on the assessment results presented in Table 4, it was found that 33 students (84.62%) achieved an overall critical thinking competency assessment at the Excellent level. This was followed by 4 students (10.26%) at the Good level, and 2 students (5.13%) at the Fair level. No students were found at the Needs Improvement level. It should be noted that students with the same overall competency level may exhibit different score patterns across the four P–I–A–C dimensions. Therefore, the interpretation of thinking quality must consider the dimensional score pattern together with the thinking traces, responses, and work products recorded in the Critical Thinking Development Activity Recording Form based on the P–I–A–C process.

The researcher selected student work samples with differing dimensional score patterns as case examples. These examples illustrate the relationship between thinking traces across the four steps of the P–I–A–C process and their corresponding results in four critical thinking dimensions. The process includes Step 1: Goal-Setting/Problem Identification (P), Step 2: Investigation Planning and Implementation (I), Step 3: Analyzing data (A), and Step 4: Conclusion and Evaluation (C). Evaluations were based on the analytic critical thinking competency assessment criteria, and the presentation is organized by the observed competency levels: Excellent, Good, and Fair. No case examples are presented for the Needs Improvement level, as no students were found at that level.

3.2.1 Students' critical thinking competency levels at the Excellent Level

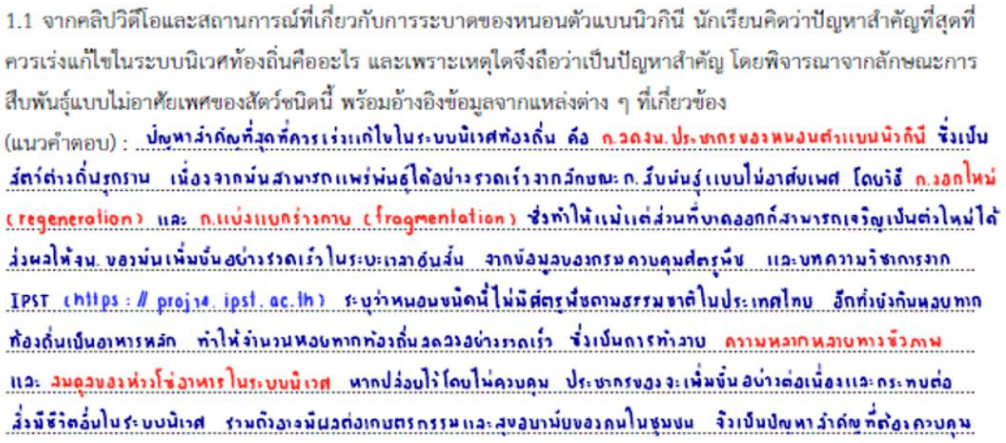
Among the 33 students who achieved an overall Excellent rating (total scores ranging from 13–16 points), ten distinct dimensional score patterns were identified. Of these, 21 students obtained the pattern 4–4–4–4 (total 16 points), indicating the highest possible rating across all four dimensions. The remaining 12 students obtained total scores ranging from 13–15 points with varying dimensional patterns. The following case examples illustrate the thinking quality underlying each score pattern; each example explains the thinking traces of that particular student and is not intended to represent all Excellent-level students.

Excellent Level in Dimensional P–I–A–C Score Profile: 4–4–4–4

Twenty-one students obtained this pattern (total 16 points), indicating full marks in all four dimensions. The researcher selected Student No. 36's activity recording form as a case example.

(1) Step 1 – Goal-Setting/Problem Identification (P): Student No. 36 received 4 points for clearly and accurately identifying the core problem—that the rapid population increase of the New Guinea flatworm affects the local ecosystem—while linking this to asexual reproduction, which facilitates rapid population growth. The student sequentially explained potential impacts on native species, biodiversity, food chains, and community livelihoods, supported by more than one credible academic and governmental source. This reflects full attainment of Level 4 criteria for problem identification, linking biological principles to real contexts, and using supporting evidence (Figure 1).

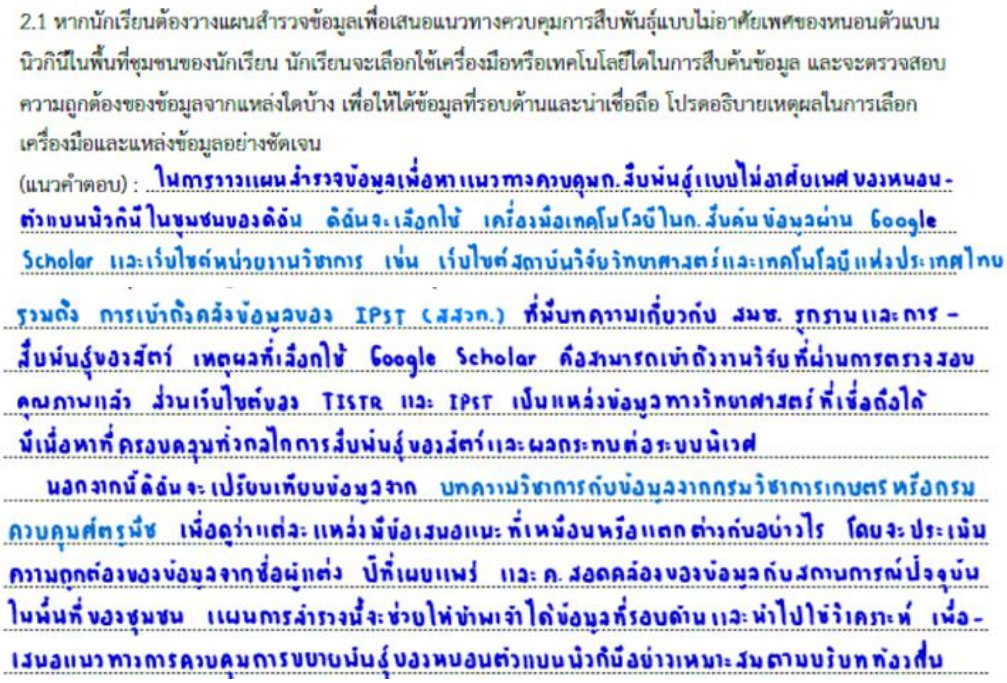
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1.1 จากคลิปวิดีโอและสถานการณ์ที่เกี่ยวกับการระบาดของหนอนตัวแบนนิวกินี นักเรียนคิดว่าปัญหาสำคัญที่สุดที่ควรเร่งแก้ไขในระบบนิเวศท้องถิ่นคืออะไร และเพราะเหตุใดจึงถือว่าเป็นปัญหาสำคัญ โดยพิจารณาจากลักษณะการสืบพันธุ์แบบไม่อาศัยเพศของสัตว์ชนิดนี้ พร้อมอ้างอิงข้อมูลจากแหล่งต่าง ๆ ที่เกี่ยวข้อง

(แนวคำตอบ) : ปัญหาสำคัญที่สุดที่ควรเร่งแก้ไขในระบบนิเวศท้องถิ่น คือ ก.วงจร.ประชากรของหนอนตัวแบนนิวกินี ซึ่งเป็นสัตว์ต่างถิ่นรุกราน เนื่องจากพบสามารถแพร่พันธุ์ได้อย่างรวดเร็วจากลักษณะ ก. สืบพันธุ์แบบไม่อาศัยเพศ โดยมี ก.งอกใหม่ (regeneration) และ ก.แบ่งแยกร่างกาย (fragmentation) ซึ่งทำให้แม้แต่ส่วนที่บาดออกก็สามารถเจริญเป็นตัวใหม่ได้ ส่งผลให้จน. ของพ้นเพิ่มขึ้นอย่างรวดเร็วในระยะเวลาอันสั้น จากข้อมูลของกรม ควบคุมศัตรูพืช และบทความวิชาการจาก IPST (https://projs.ipst.ac.th) ระบุว่าหนอนชนิดนี้ไม่มีศัตรูพืชตามธรรมชาติในประเทศไทย อีกทั้งยังกินหอยทากท้องถิ่นเป็นอาหารหลัก ทำให้จำนวนหอยทากท้องถิ่นลดลงอย่างรวดเร็ว ซึ่งเป็นการทำลาย ความหลากหลายทางชีวภาพ และ สมดุลของห่วงโซ่อาหารในระบบนิเวศ หากปล่อยไว้โดยไม่ควบคุม ประชากรของจะเพิ่มขึ้นอย่างต่อเนื่องและกระทบต่อสิ่งมีชีวิตอื่นในระบบนิเวศ รวมถึงการเพิ่มต่อเกษตรกรรม และ สุขอนามัยของคนในชุมชน จึงเป็นปัญหาสำคัญที่ต้องควบคุม

Figure 1: Student No. 36' s problem identification, linking biological principles to real contexts, and using supporting evidence

(2) Step 2 – Investigation Planning and Implementation (I): The student received 4 points for systematically planning information searches using Google Scholar and academic institutional websites, drawing on at least two sources, comparing research data with governmental data, and establishing credibility criteria (author/organization, publication year, relevance to current community context). This reflects full Level 4 attainment for tool selection, multi-source data planning, and quality verification (Figure 2).


2.1 หากนักเรียนต้องวางแผนสำรวจข้อมูลเพื่อเสนอแนวทางควบคุมการสืบพันธุ์แบบไม่อาศัยเพศของหนอนตัวแบนนิวกินีในพื้นที่ชุมชนของนักเรียน นักเรียนจะเลือกใช้เครื่องมือหรือเทคโนโลยีใดในการสืบค้นข้อมูล และจะตรวจสอบความถูกต้องของข้อมูลจากแหล่งใดบ้าง เพื่อให้ได้ข้อมูลที่รอบด้านและน่าเชื่อถือ โปรดอธิบายเหตุผลในการเลือกเครื่องมือและแหล่งข้อมูลอย่างชัดเจน

(แนวคำตอบ) : ในการวางแผนสำรวจข้อมูลเพื่อหาแนวทางควบคุม ก.สืบพันธุ์แบบไม่อาศัยเพศ ของหนอนตัวแบนนิวกินี ในชุมชนของดิฉัน ดิฉันจะเลือกใช้ เครื่องมือเทคโนโลยีใน ก.สืบค้นข้อมูลผ่าน Google Scholar และเว็บไซต์หน่วยงานวิชาการ เช่น เว็บไซต์สถาบันวิจัยวิทยาศาสตร์และเทคโนโลยีแห่งประเทศไทย รวมถึง การเข้าถึงคลังข้อมูลของ IPST (สวทช.) ที่มีบทความเกี่ยวกับ สมช. รุกรานและการสืบพันธุ์ของสัตว์ เหตุผลที่เลือกใช้ Google Scholar คือสามารถเข้าถึงงานวิจัยที่ผ่านการตรวจสอบคุณภาพแล้ว ส่วนเว็บไซต์ของ TISTR และ IPST เป็นแหล่งข้อมูลทางวิทยาศาสตร์ที่เชื่อถือได้ มีเนื้อหาที่ครอบคลุมทั้งกลไกการสืบพันธุ์ของสัตว์และผลกระทบต่อระบบนิเวศ

นอกจากนี้ดิฉันจะเปรียบเทียบข้อมูลจาก บทความวิชาการกับข้อมูลจากกรมวิชาการเกษตร หรือกรมควบคุมศัตรูพืช เพื่อดูว่าแต่ละแหล่งมีข้อเสนอแนะที่เหมือนหรือแตกต่างกันอย่างไร โดยจะประเมินความถูกต้องของข้อมูลจากชื่อผู้แต่ง ปีที่เผยแพร่ และ ค. สอดคล้องของข้อมูลกับสถานการณ์ปัจจุบันในพื้นที่ของชุมชน แผนการสำรวจนี้จะช่วยให้ทำเจาได้ข้อมูลที่รอบด้าน และนำไปใช้วิเคราะห์ เพื่อเสนอแนวทางการควบคุมการขยายพันธุ์ของหนอนตัวแบนนิวกินีอย่างเหมาะสมตามบริบทท้องถิ่น

Figure 2: Student No. 36' s tool selection, multi-source data planning, and quality verification

(3) Step 3 – Analyzing data (A): The student received 4 points for using evidence on asexual reproduction to explain rapid population growth and logically linking this to impacts on native species, biodiversity, food chains, and ecosystem balance. The student

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proposed control approaches considering both expected outcomes and impacts on other organisms, and evaluated the credibility, appropriateness, and sufficiency of the evidence used—fully meeting Level 4 criteria (Figure 3).

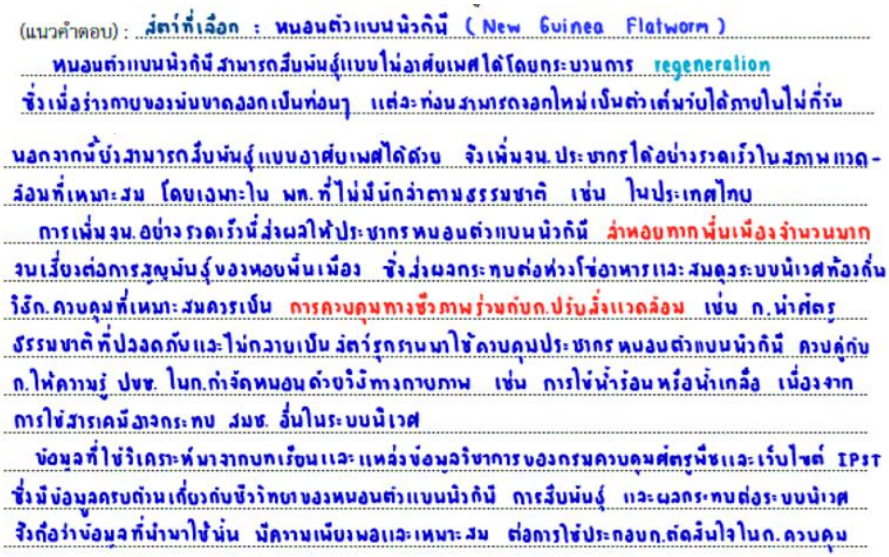


Figure 3: Student No. 36' s control approaches considering both expected outcomes and impacts organisms, and evaluated the credibility, appropriateness, and sufficiency of the evidence used

(4) Step 4 – Conclusion and Evaluation (C): The student received 4 points for making an evidence-based decision regarding control methods, weighing benefits, limitations, and potential impacts of biological control, while proposing community education and participation as supporting strategies. The decision considered safety, feasibility, sustainability, and contextual appropriateness—fully meeting Level 4 criteria (Figure 4).

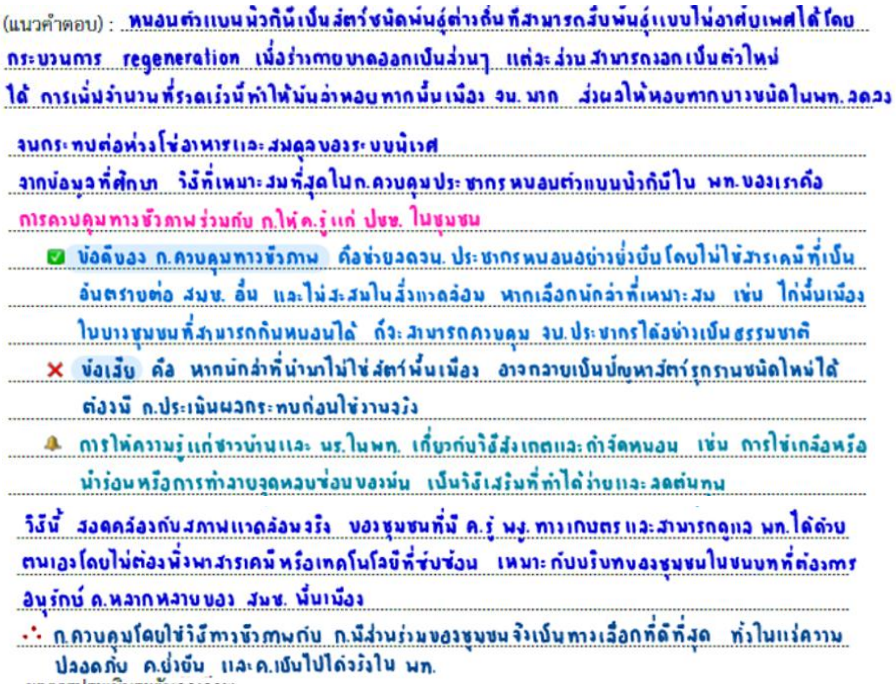


Figure 4: Student No. 36' s decision considered safety, feasibility, sustainability, and contextual appropriateness

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Excellent Level in Dimensional P–I–A–C Score Profile: 3–4–4–4

Three students (7.69%) obtained this pattern (total 15 points), indicating Level 4 attainment in I, A, and C, with Level 3 in P. Student No. 29 was selected as the case example.

(1) P (3 points): The student accurately identified the problem and reasonably linked it to asexual reproduction, explaining impacts on native snails and ecosystem balance. However, the response lacked clear reference to diverse data sources and did not elaborate sufficiently on biological mechanisms, falling short of Level 4 criteria.

(2) I (4 points): The student systematically planned searches using Google Scholar together with TISTR and IPST websites, drawing on more than two sources and establishing credibility criteria including author/organization, publication year, and consistency across sources.

(3) A (4 points): The student logically explained population increase and spread using biological evidence, linked this to impacts on native snails, biodiversity, and ecosystem balance, and evaluated the credibility, appropriateness, and sufficiency of evidence.

(4) C (4 points): The student made an evidence-based decision considering benefits, limitations, and risks of biological control, as well as feasibility within community resources.

The overall thinking trace is consistent with the 3–4–4–4 pattern (15 points); the limitation appeared only in P due to insufficient source diversity and mechanistic explanation. This interpretation applies solely to Student No. 29.

Excellent Level in Dimensional Score Pattern P–I–A–C = 4–4–3–4

One student (2.56%) obtained this pattern (total 15 points). Student No. 34 was selected as the case example.

(1) P (4 points): The student clearly identified the problem, linking population increase to fragmentation and regeneration, supported by multiple credible sources, and comprehensively addressed impacts on native species, biodiversity, food chains, agriculture, and community hygiene.

(2) I (4 points): The student systematically planned searches using research databases and credible academic websites, drawing on more than two sources and verifying consistency between academic and governmental data

(3) A (3 points): The student used information about hermaphroditism and egg-laying in the Giant African land snail to explain population increase, logically linking this to ecosystem and agricultural impacts. However, a significant limitation emerged: the student shifted the case study from the New Guinea flatworm to the Giant African land snail, disrupting continuity with the problem identified in Step P. Furthermore, hermaphroditism and egg-laying are characteristics of sexual reproduction rather than asexual reproduction. Since asexual reproduction is the core concept of this activity, this discrepancy results in an incomplete alignment with Level 4 criteria.

(4) C (4 points): The student returned to using scientific evidence on asexual reproduction to justify their chosen control method for the New Guinea flatworm. Their justification considered the benefits, limitations, and impacts of biological control, as well as community participation. Consequently, this work fully meets the Level 4 criteria.

Overall, the thinking trace is consistent with the 4–4–3–4 pattern (15 points), with the limitation confined to Step A due to case inconsistency and a biological inaccuracy regarding reproductive mode. This interpretation applies solely to Student No. 34.

Excellent Level in Dimensional P–I–A–C Score Profile: 4–3–4–4

One student (2.56%) obtained this pattern (total 15 points). Student No. 27 was selected as the case example.

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(1) P (4 points): The student clearly identified the problem, linking it to fragmentation and regeneration with supporting evidence from multiple credible sources, and comprehensively addressed ecosystem impacts—fully meeting Level 4 criteria

(2) I (3 points): The student planned searches using the internet and online video sources, drawing on at least two sources with basic credibility consideration. However, the plan did not clearly demonstrate verification against research databases or official sources, nor did it comprehensively cover long-term ecological impacts and control approaches, falling short of Level 4 criteria.

(3) A (4 points): The student accurately and systematically used scientific evidence on asexual reproduction to explain population increase, linking this directly to ecosystem impacts. Additionally, they proposed biologically consistent control approaches and evaluated evidence credibility and sufficiency. As a result, this response fully meets Level 4 criteria.

3.2.2 Students' critical thinking competency levels at the Good Level

As shown in Table 4, four students demonstrated an overall "Good" level of critical thinking competency. These students represent 10.26% of the total sample. Across the P–I–A–C framework, their scores yielded four distinct configurations: 4–4–1–3, 3–2–3–3, 4–1–1–4, and 4–3–2–1 (one student per profile). Overall, their composite scores ranged from 10 to 12 points. These diverse score distributions illustrate that individual learners possessed distinct cognitive strengths and limitations across the specific dimensions of critical thinking.

Consequently, the researcher examined representative student work samples corresponding to each score configuration as specific case studies. These analyses delineate the students' underlying cognitive traces and provide an evidence-based rationale for the assessment ratings according to the analytic P–I–A–C rubric. Importantly, findings derived from each individual case are intended exclusively to explicate the quality of critical thinking exhibited by that specific student, rather than serving as generalized representations of all students categorized within the "Good" performance tier.

Good Level in Dimensional P–I–A–C Score Profile: 4–4–1–3

Based on Table 4, one student (2.56%) attained a composite score of 12 points, characterized by a dimensional breakdown of 4, 4, 1, and 3 across the P, I, A, and C stages, respectively. The critical thinking learning artifact of Student No. 4 was selected as an exemplar case to illustrate cognitive performance across all four stages of the inquiry process and to substantiate the assigned analytic scores:

(1) Stage 1: Problem Posing and Goal Setting (P)

Student No. 4 earned a score of 4. The student clearly and accurately identified the core issue presented in the scenario: the rapid population surge of the New Guinea flatworm (Platydemus manokwari) and its deleterious impacts on local ecosystems. Crucially, the student linked this phenomenon to biological mechanisms—specifically binary fission and regeneration as modes of asexual reproduction facilitating rapid proliferation and geographic dispersion. Furthermore, the student systematically articulated the ecological ramifications on native snail species, regional biodiversity, and trophic food webs, while logically extending this analysis to agricultural productivity and community sanitation. The problem formulation was thoroughly substantiated by multiple authoritative sources, including official government agencies and peer-reviewed academic literature. This artifact demonstrates the capacity to formulate problems systematically, integrate core biological principles with real-world phenomena, and utilize verified multi-source evidence in full alignment with Level 4 criteria (see Figure 5).

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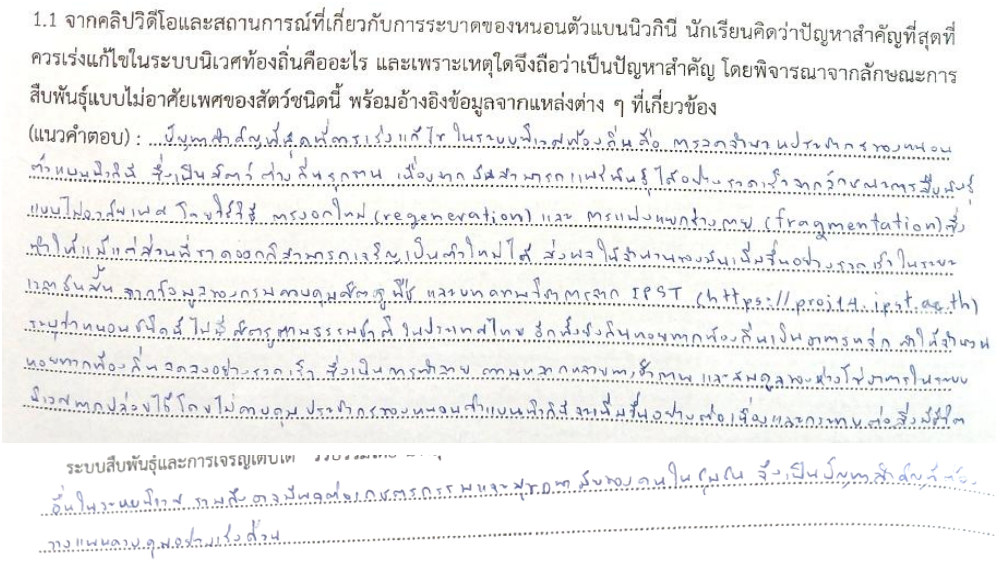


Figure 5: Evidence of Student No. 4's thinking in Stage P, showing the identification of the New Guinea flatworm population increase linked to asexual reproduction, local ecosystem impacts, and data from multiple credible sources.

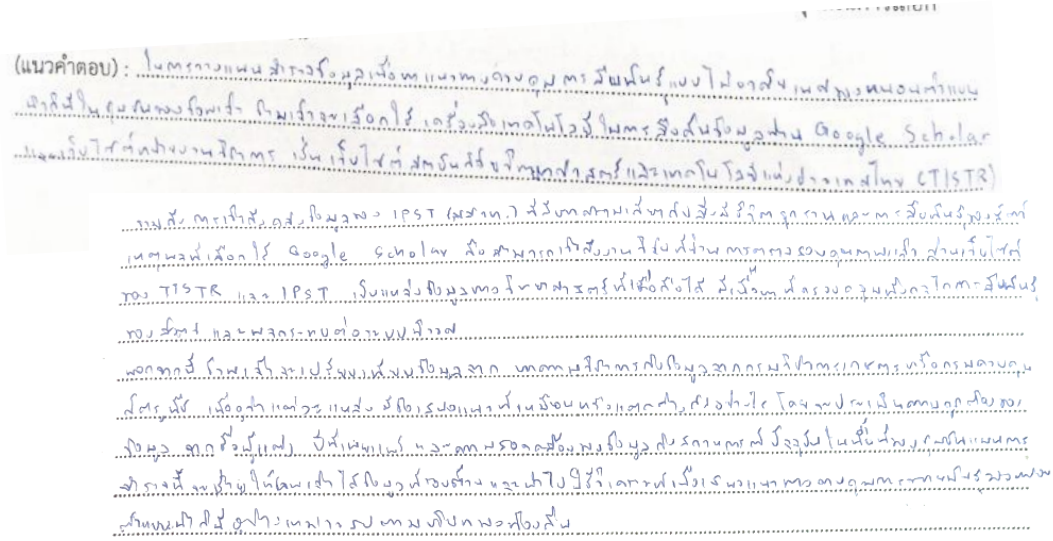


Figure 6: Student 4's thinking traces in Dimension I, demonstrating information retrieval planning from academic databases and credible agency websites, alongside the verification of authorship, publication year, and alignment with the local context.

(2) Stage 2: Information Seeking and Planning (I)

Student No. 4 earned a score of 4. The student formulated a rigorous, systematic inquiry strategy by selecting institutional repositories and academic databases to gather empirical data concerning the reproduction, population dynamics, and ecological consequences of the New Guinea flatworm. Explicit rationales were provided for the selection of each source type. Furthermore, the student applied comprehensive source-criticism criteria, evaluating authorship, institutional credibility, publication timeliness, and geographic contextual relevance. These traces demonstrate advanced competence in selecting research instruments, executing multi-source data collection plans, and

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systematically verifying source credibility in complete accordance with Level 4 criteria (see Figure 6).

(3) Stage 3: Data Analysis and Processing (A)

Student No. 4 earned a score of 1. The student's analysis was predominantly driven by subjective emotional responses (e.g., expressions of fear and revulsion) rather than rigorous empirical examination. Notably, the artifact lacked scientific evidence pertaining to asexual reproduction mechanisms. The student failed to explicate how fission and regeneration drive population dynamics and omitted logical connections between rapid proliferation and the resultant disruptions to native snail populations, food web stability, or ecosystem equilibrium. Proposed mitigation strategies were disconnected from foundational biological principles, with no appraisal of ecological impacts, source sufficiency, or methodological appropriateness. Consequently, this performance reflected an inability to analyze scientific data analytically, corresponding to Level 1 (see Figure 7).

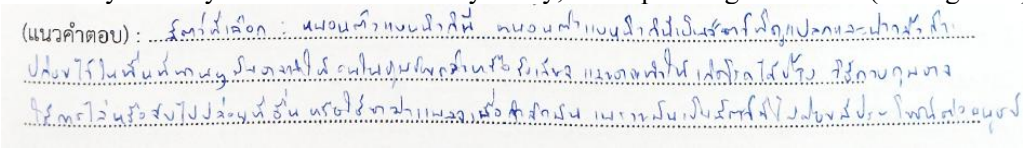


Figure 7: Cognitive traces of Student No. 4 in Stage A (Score: 1), characterized by subjective emotional judgments lacking scientific evidence concerning asexual reproduction, ecological ramifications, or evidence-based control measures.

(4) Stage 4: Conclusion Drawing and Evaluation (C)

Student No. 4 earned a score of 3. The student exhibited sound reasoning in selecting a control strategy for the Giant African Snail, integrating data on population dynamics with ecological and public health consequences. The evaluation weighed both the benefits and constraints of chemical treatment (metaldehyde), balancing immediate population reduction efficacy against prospective non-target toxicity and environmental hazards. However, an abrupt shift in focus occurred: the student transitioned from the New Guinea flatworm (established in Stage P) to the Giant African Snail, disrupting conceptual continuity and detaching the response from the designated asexual reproduction theme. Additionally, while recognizing chemical limitations, the student failed to formulate viable alternatives adapted to natural ecosystem dynamics. This partial contextual integration met the criteria for Level 3 (see Figure 8).

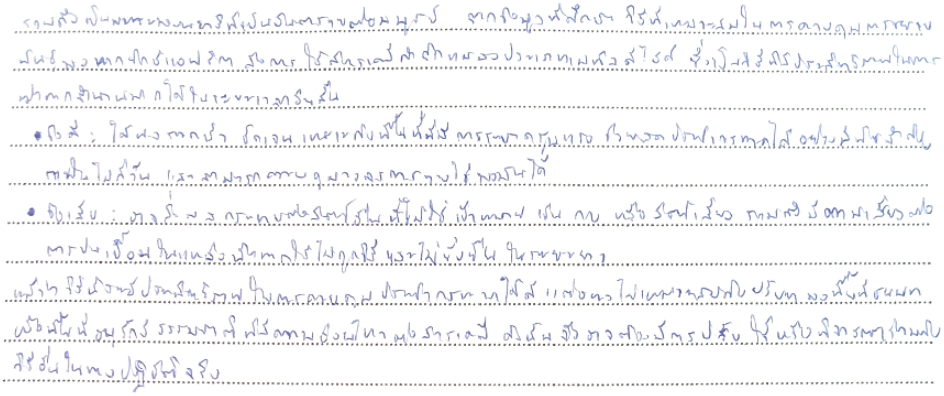


Figure 8 Cognitive traces of Student No. 4 in Stage C (Score: 3), showing an evaluative decision regarding chemical control (metaldehyde) that considered utility and ecotoxicity, but exhibited limitations in conceptual continuity and environmental contextualization.

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Cross-dimensional synthesis confirms exemplary competence in problem definition (Stage P) and systematic inquiry planning (Stage I). However, cognitive quality bifurcated at Stage A, where objective scientific analysis was superseded by subjective sentiment, before partially recovering at Stage C with balanced but contextually discontinuous evaluative decision-making. This performance profile substantiates the 4–4–1–3 configuration (composite score: 12) and underscores the non-linear distribution of critical thinking abilities within an individual learner.

Good Level in Dimensional P–I–A–C Score Profile: 3–2–3–3

Based on Table 4, one student (2.56%) achieved a composite score of 11 points, with a dimensional sequence of 3, 2, 3, and 3 across the P, I, A, and C stages, respectively. The learning artifact of Student No. 18 serves as an illustrative case:

(1) Stage 1: Problem Posing and Goal Setting (P)

Student No. 18 earned a score of 3. The student accurately articulated the focal problem, identifying the rapid proliferation of the New Guinea flatworm and its adverse impacts on local biodiversity. The response properly associated this population explosion with asexual reproductive mechanisms (fission and regeneration) and logically described the consequences for native snails and ecological balance. Nevertheless, the response lacked concrete empirical citations or external academic backing, precluding the comprehensive evidentiary depth required for Level 4. Performance was thus rated at Level 3.

(2) Stage 2: Information Seeking and Planning (I)

Student No. 18 earned a score of 2. The student identified appropriate tools for scientific information retrieval, including Google Scholar and official governmental portals. However, the execution trace revealed reliance on a single primary source without comparative triangulation across multiple references. While expressing uncertainty regarding source credibility, the student established no systematic verification criteria concerning author expertise, institutional affiliation, or publication year. The inquiry plan lacked the necessary comprehensiveness to robustly support downstream analysis, aligning with Level 2.

(3) Stage 3: Data Analysis and Processing (A)

Student No. 18 earned a score of 3. The student applied reproductive biological data of the Giant African Snail to explain population expansions and associated ecosystem and anthropocentric consequences, proposing moderately feasible control approaches. However, conceptual continuity was compromised by shifting the focus organism from the flatworm (Stage P) to the snail. Furthermore, the analysis exhibited a fundamental biological misconception: classifying hermaphroditism and oviparous egg-laying as forms of asexual reproduction, rather than sexual reproduction. The artifact also lacked comparative data appraisal, restricting the score to Level 3.

(4) Stage 4: Conclusion Drawing and Evaluation (C)

Student No. 18 earned a score of 3. The student made an evidence-informed decision regarding flatworm population management, evaluating both advantages and operational constraints while demonstrating awareness of potential non-target ecological impacts. However, the evaluation prioritized immediate, short-term reduction over long-term ecological sustainability, failing to propose conservation-aligned mitigations tailored to rural or protected natural habitats. These constraints positioned the response at Level 3.

Student No. 18 demonstrated consistent intermediate-to-advanced reasoning across all phases, effectively recognizing ecological problems and evaluating trade-offs. However, developmental deficits in source verification protocols (Stage I) and persistent conceptual misconceptions regarding reproductive biology (Stage A) constrained overall performance, corroborating the 3–2–3–3 profile (composite score: 11).

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Good Level in Dimensional P–I–A–C Score Profile: 4–1–1–4

Based on Table 4, one student (2.56%) attained a composite score of 10 points, reflecting a polarized dimensional configuration of 4, 1, 1, and 4 across the respective P, I, A, and C stages. The work sample of Student No. 6 illustrates this bifurcated pattern:

(1) Stage 1: Problem Posing and Goal Setting (P)

Student No. 6 earned a score of 4. The student clearly and comprehensively defined the core environmental challenge: the exponential growth of the New Guinea flatworm population. The problem framework accurately integrated principles of asexual reproduction (fission and regenerative capacity) as the primary engine of spread. The systemic cascade across native fauna, biodiversity loss, and community balance was articulated systematically and substantiated by verified governmental and academic references, fulfilling all criteria for Level 4.

(2) Stage 2: Information Seeking and Planning (I)

Student No. 6 earned a score of 1. The student failed to formulate a structured inquiry plan aligned with academic research objectives. The strategy relied entirely on generic mobile searches without specifying keywords, search operators, or scholarly repositories. Suggested sources included unvetted social media platforms (TikTok) and peer consultations. No evaluative metrics were established to appraise validity, authority, or consistency. Despite utilizing verified information in Stage P, the student could not outline an operationalized, systematic method for acquiring evidence, warranting a rating of Level 1.

(3) Stage 3: Data Analysis and Processing (A)

Student No. 6 earned a score of 1. The analytical output relied heavily on subjective emotional perspectives rather than objective empirical synthesis. The student omitted biological explanations regarding fission mechanisms and population kinetics, and provided no reasoned causal links connecting proliferation to native species decline or broader ecological imbalance. Proposed control methods lacked empirical foundation, and no assessment of environmental impact or data adequacy was conducted. This absence of scientific analysis placed the performance at Level 1.

(4) Stage 4: Conclusion Drawing and Evaluation (C)

Student No. 6 earned a score of 4. The student demonstrated an advanced capacity for evidence-based decision-making. The final evaluation synthesized biological concepts (fission/regeneration rates) to recommend targeted biological controls while explicitly analyzing constraints, non-target species introduction hazards, and overall system risks. Furthermore, the decision integrated community education and local participation, reflecting a sophisticated balance of local feasibility, biosecurity, and ecological sustainability. This comprehensive, multi-criteria appraisal fulfilled all Level 4 criteria.

Student No. 6 presented a starkly polarized cognitive profile. While demonstrating exceptional proficiency in conceptualizing problems (Stage P) and formulating holistic, evidence-based conclusions (Stage C), the student exhibited pronounced deficiencies in information retrieval planning (Stage I) and intermediate scientific data analysis (Stage A). This distinct polarity confirms the 4–1–1–4 profile (composite score: 10) and demonstrates that high-order evaluative competence can operate independently of formal information seeking and preliminary data processing skills.

Good Level in Dimensional P–I–A–C Score Profile: 4–3–2–1

Based on Table 4, one student (2.56%) recorded a composite score of 10 points, exhibiting a progressively declining dimensional profile of 4, 3, 2, and 1 across stages P, I, A, and C, respectively. The learning record of Student No. 2 highlights this downward cognitive trajectory:

(1) Stage 1: Problem Posing and Goal Setting (P)

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Student No. 2 earned a score of 4. The student precisely articulated the ecological threat posed by the New Guinea flatworm, establishing clear causal connections between its asexual reproduction and rapid population proliferation. The analysis incorporated critical ecological dynamics—including the absence of natural apex predators, intense predation on native gastropods, and resultant shifts in ecosystem biodiversity. The problem statement was rigorously supported by authoritative governmental and academic data, meeting all requirements for Level 4.

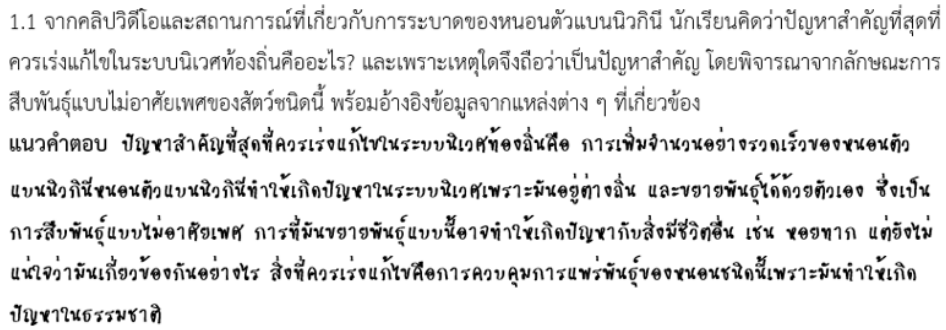
3.2.3 Students' critical thinking competency levels at the Fair Level

As indicated in Table 4, two students (5.13% of the total sample) demonstrated an overall "Fair" level of critical thinking competency. Across the P–I–A–C framework, they exhibited two distinct dimensional score profiles: 2–2–2–2 and 4–1–1–1 (one student per profile). Their resulting composite scores ranged from 7 to 8 points. These evaluation outcomes demonstrate that individual learners possessed distinct developmental proficiencies and cognitive limitations across the specific phases of the critical thinking process.

To provide a detailed diagnostic account, the researcher examined representative student work samples corresponding to each score configuration as descriptive case studies. These analyses explicate the underlying cognitive traces and provide an empirical justification for the ratings based on the analytic P–I–A–C rubric. It should be emphasized that the findings from each case serve exclusively to characterize the thinking quality of that specific learner and are not intended to represent the entire cohort of students evaluated at the "Fair" level.

Fair Level in Dimensional P–I–A–C Score Profile: 2–2–2–2

Based on Table 4, one student (2.56%) achieved a composite score of 8 points, characterized by an evenly distributed dimensional rating of 2 across all four stages (P, I, A, and C). The critical thinking record of Student No. 7 was selected as an illustrative case to trace cognitive performance across the inquiry continuum:


1.1 จากคลิปวิดีโอและสถานการณ์ที่เกี่ยวกับการระบาดของหนอนตัวแบนนิวกินี นักเรียนคิดว่าปัญหาสำคัญที่สุดที่ควรเร่งแก้ไขในระบบนิเวศท้องถิ่นคืออะไร? และเพราะเหตุใดจึงถือว่าเป็นปัญหาสำคัญ โดยพิจารณาจากลักษณะการสืบพันธุ์แบบไม่อาศัยเพศของสัตว์ชนิดนี้ พร้อมอ้างอิงข้อมูลจากแหล่งต่าง ๆ ที่เกี่ยวข้อง

แนวคำตอบ ปัญหาสำคัญที่สุดที่ควรเร่งแก้ไขในระบบนิเวศท้องถิ่นคือ การเพิ่มจำนวนอย่างรวดเร็วของหนอนตัวแบนนิวกินีหนอนตัวแบนนิวกินีทำให้เกิดปัญหาในระบบนิเวศเพราะมันอยู่ต่างถิ่น และขยายพันธุ์ได้ด้วยตัวเอง ซึ่งเป็นการสืบพันธุ์แบบไม่อาศัยเพศ การที่มันขยายพันธุ์แบบนี้อาจทำให้เกิดปัญหากับสิ่งมีชีวิตอื่น เช่น หอยทาก แต่ยังไม่แน่ใจว่ามันเกี่ยวข้องกันอย่างไร สิ่งที่ควรเร่งแก้ไขคือการควบคุมการแพร่พันธุ์ของหนอนชนิดนี้เพราะมันทำให้เกิดปัญหาในธรรมชาติ

Figure 9: Cognitive traces of Student No. 7 in Stage P (Score: 2), showing partial problem identification regarding flatworm proliferation and asexual reproduction, but lacking detailed ecological impact assessments and empirical substantiation.

(1) Stage 1: Problem Posing and Goal Setting (P)

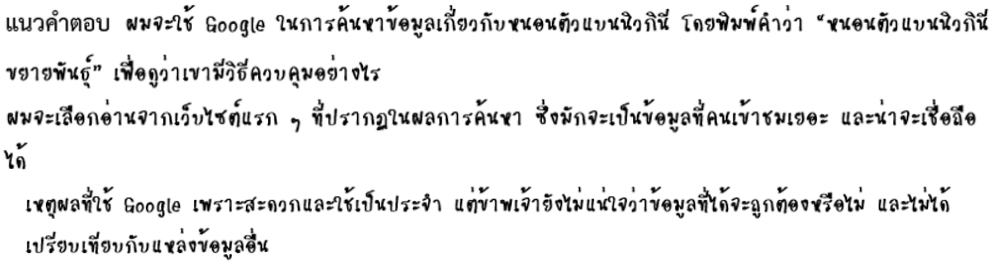
Student No. 7 earned a score of 2. The student partially identified the core problem regarding the rapid population growth of the New Guinea flatworm (Platydemus manokwari), broadly connecting it to its invasive status and asexual reproductive characteristics. However, the explanatory rationale lacked clarity and logical coherence. The student could not concretely articulate the causal mechanisms linking population growth to the depletion of native snails, broader ecological imbalances, or trophic cascades. The impact assessment remained superficial and was unsupported by verified

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external citations or empirical evidence. Consequently, the performance demonstrated partial problem identification without the comprehensive, evidence-based reasoning required for Level 3, warranting a rating of Level 2 (see Figure 9).

(2) Stage 2: Information Seeking and Planning (I)

Student No. 7 earned a score of 2. The student demonstrated a rudimentary information search plan by utilizing Google as a primary search interface to locate general information on the New Guinea flatworm. However, the execution relied entirely on a single web source, with credibility inferred merely from the search engine's ranking order rather than scholarly verification standards. The student did not cross-reference multiple sources, nor did they evaluate author credentials, institutional authority, publication date, or contextual applicability. This uncritical reliance on unverified single-source data restricted the quality of the information gathered, placing the performance at Level 2 (see Figure 10).


แนวคำตอบ ผมจะใช้ Google ในการค้นหาข้อมูลเกี่ยวกับหนอนตัวแบนนิวกินี โดยพิมพ์คำว่า "หนอนตัวแบนนิวกินี ขยายพันธุ์" เพื่อดูว่าเขามีวิธีควบคุมอย่างไร

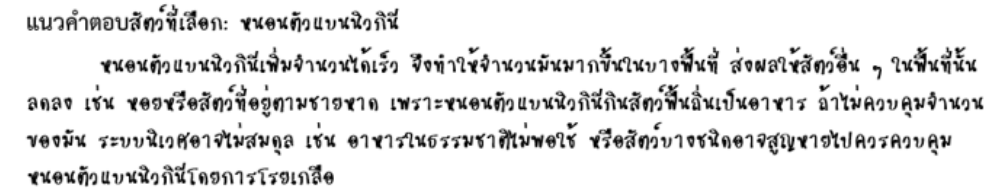
ผมจะเลือกอ่านจากเว็บไซต์แรก ๆ ที่ปรากฏในผลการค้นหา ซึ่งมักจะเป็นข้อมูลที่คนเข้าชมเยอะ และน่าจะเชื่อถือได้

เหตุผลที่ใช้ Google เพราะสะดวกและใช้เป็นประจำ แต่ข้าพเจ้ายังไม่แน่ใจว่าข้อมูลที่ได้จะถูกต้องหรือไม่ และไม่ได้เปรียบเทียบกับแหล่งข้อมูลอื่น

Figure 10: Cognitive traces of Student No. 7 in Stage I (Score: 2), demonstrating basic retrieval using Google restricted to a single primary source, without cross-validation or academic credibility criteria.

(3) Stage 3: Data Analysis and Processing (A)

Student No. 7 earned a score of 2. The student recognized that the New Guinea flatworm is an invasive species capable of rapid expansion and disruptive to native snail biodiversity. A practical control method was proposed—specifically, the direct application of table salt (sodium chloride). However, the analysis failed to link this intervention to the flatworm's cellular fission or regenerative capacities. Furthermore, the student provided no empirical evidence to validate the efficacy or ecological suitability of salt application, omitting critical appraisals of secondary environmental consequences, such as soil salinization, phytotoxicity, and mortality among non-target soil organisms. Because the analysis lacked systematic scientific evaluation, it was scored at Level 2 (see Figure 11).


แนวคำตอบสัตว์ที่เลือก: หนอนตัวแบนนิวกินี

หนอนตัวแบนนิวกินีเพิ่มจำนวนได้เร็ว จึงทำให้จำนวนมันมากขึ้นในบางพื้นที่ ส่งผลให้สัตว์อื่น ๆ ในพื้นที่นั้นลดลง เช่น หอยหรือสัตว์ที่อยู่ตามรายทาง เพราะหนอนตัวแบนนิวกินีกินสัตว์พื้นถิ่นเป็นอาหาร ถ้าไม่ควบคุมจำนวนของมัน ระบบนิเวศอาจไม่สมดุล เช่น อาหารในธรรมชาติไม่พอใช้ หรือสัตว์บางชนิดอาจสูญพันธุ์ไปควรควบคุมหนอนตัวแบนนิวกินีโดยการโรยเกลือ

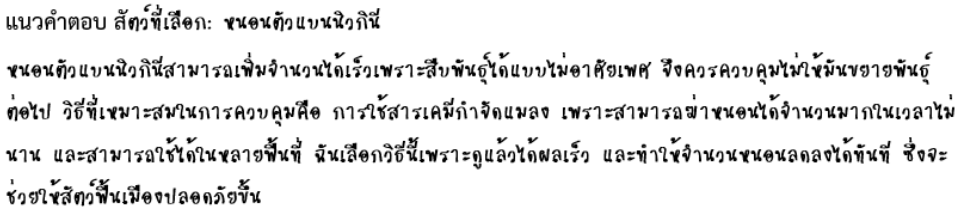
Figure 11: Cognitive traces of Student No. 7 in Stage A (Score: 2), outlining flatworm proliferation and suggesting chemical/salt eradication, but failing to evaluate biological mechanisms, secondary environmental toxicity, or data adequacy.

(4) Stage 4: Conclusion Drawing and Evaluation (C)

Student No. 7 earned a score of 2. The student made a management decision by selecting chemical control methods to address rapid population growth, emphasizing immediate practical advantages such as rapid action and convenience. However, the justification was limited to short-term extermination metrics. The student omitted

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comprehensive analyses of adverse impacts on native gastropods, soil and aquatic chemistry, and overall ecosystem stability. Furthermore, the decision lacked alignment with the ecological sensitivity of local habitats, and included no comparative evaluation of alternative, sustainable interventions. Because the decision was only partially reasoned and neglected systematic risk appraisal, it was evaluated at Level 2 (see Figure 12).


แนวคำตอบ สัตว์ที่เลือก: หนอนตัวแบนนิวกินี

หนอนตัวแบนนิวกินีสามารถเพิ่มจำนวนได้เร็วเพราะสืบพันธุ์ได้แบบไม่อาศัยเพศ จึงควรควบคุมไม่ให้มันขยายพันธุ์ต่อไป วิธีที่เหมาะสมในการควบคุมคือ การใช้สารเคมีกำจัดแมลง เพราะสามารถฆ่าหนอนได้จำนวนมากในเวลาไม่นาน และสามารถใช้ได้ในหลายพื้นที่ ฉันเลือกวิธีนี้เพราะดูแล้วได้ผลเร็ว และทำให้จำนวนหนอนลดลงได้ทันที ซึ่งจะช่วยให้สัตว์พื้นเมืองปลอดภัยขึ้น

Figure 12: Cognitive traces of Student No. 7 in Stage C (Score: 2), illustrating a control decision focused primarily on short-term efficacy, without multidimensional assessments of ecotoxicity, habitat context, or long-term sustainability.

Student No. 7 demonstrated an entry-level capacity to navigate all four stages of the inquiry process, showing basic awareness of invasive species dynamics and control options. However, cognitive performance was consistently constrained by superficial problem framing (Stage P), unverified single-source retrieval (Stage I), unsystematic biological analysis (Stage A), and short-sighted evaluative decision-making (Stage C). This uniform, baseline performance across all dimensions directly substantiates the 2–2–2–2 score profile (composite score: 8).

Fair Level in Dimensional P–I–A–C Score Profile: 4–1–1–1

Based on Table 4, one student (2.56%) achieved a composite score of 7 points, presenting an asymmetric score distribution of 4, 1, 1, and 1 across stages P, I, A, and C, respectively. The learning artifact of Student No. 5 illustrates this pattern of high initial performance followed by cognitive discontinuity:

(1) Stage 1: Problem Posing and Goal Setting (P)

Student No. 5 earned a score of 4. The student accurately and comprehensively defined the core environmental challenge: the exponential population expansion of the New Guinea flatworm and its systemic disruption of local ecosystems. The problem formulation integrated biological mechanisms, explicitly linking binary fission and anatomical regeneration to rapid propagation and dispersal. Furthermore, the student logically articulated the downstream ecological cascades affecting native biodiversity, trophic food webs, and ecosystem stability, supporting the formulation with multiple credible institutional and academic references. This performance fulfilled all requirements for Level 4.

(2) Stage 2: Information Seeking and Planning (I)

Student No. 5 earned a score of 1. The student failed to design a systematic data collection strategy, stating only an intention to conduct generic mobile internet searches. The artifact lacked essential search parameters, including academic databases, specific keywords, thematic sub-topics, and operational milestones. Moreover, the student established no criteria for assessing source credibility (e.g., author credentials, institutional authority, publication date, or local contextual relevance) and included no plan for cross-referencing information. Despite incorporating verified data in Stage P, the student could not operationalize an inquiry plan to systematically gather evidence, warranting a rating of Level 1.

(3) Stage 3: Data Analysis and Processing (A)

Student No. 5 earned a score of 1. The analytical output relied on affective perceptions and generalized public anxieties (e.g., perceived danger and disease risk)

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rather than empirical scientific analysis. The student did not analyze the biological mechanisms of fission and regeneration relative to population growth, nor did they establish causal connections between rapid propagation and disruptions to native biodiversity, trophic webs, or ecosystem equilibrium. Proposed mitigation strategies were unlinked to biological data and lacked empirical support from verified sources, with no evaluation of data adequacy. This absence of evidence-based reasoning resulted in a rating of Level 1.

(4) Stage 4: Conclusion Drawing and Evaluation (C)

Student No. 5 earned a score of 1. The student proposed managing the blue hermit crab (Clibanarius sp.) via physical relocation, failing to provide a scientific rationale to support the decision. The justification prioritized human convenience rather than ecological balance, food web stability, or biodiversity preservation. Furthermore, this response introduced a conceptual discontinuity by shifting the focal organism from the New Guinea flatworm (Stage P) to the hermit crab. This shift also revealed a fundamental biological error: misattributing asexual reproduction to hermit crabs, which reproduce sexually. The proposed relocation also ignored critical ecological risks, such as introducing invasives to recipient habitats or subsequent recolonization. Lacking empirical substantiation and systemic risk appraisal, this performance was rated at Level 1.

Cross-dimensional synthesis revealed a sharp divergence in Student No. 5's cognitive performance. While the student demonstrated advanced proficiency in initial problem identification and systemic biological framing (Stage P, Level 4), performance dropped across all subsequent inquiry phases. The student was unable to construct a systematic search plan (Stage I), substituted subjective emotional perceptions for empirical analysis (Stage A), and produced an unsubstantiated, conceptually discontinuous conclusion containing basic biological errors (Stage C). This marked divergence between initial problem awareness and subsequent analytical execution directly validates the 4–1–1–1 score profile (composite score: 7).

4.Conclusion and Discussion

This study examined the effects of the revised CT-HOT in Bio instructional innovation on the critical thinking competency of Grade 12 students during the second implementation phase (R3, Academic Year 2025), using the topic of asexual reproduction in invasive alien species as the instructional context. The findings demonstrate that the innovation was highly effective in cultivating critical thinking competency.

These results indicate that most students were able to engage in the full cycle of critical thinking operationalized through the P-I-A-C framework. First, they successfully identified problems by connecting biological mechanisms (fragmentation, regeneration) to real-world ecological and socioeconomic consequences, followed by planning systematic investigations using multiple credible sources. Finally, they analyzed data by linking scientific principles to proposed solutions, concluding with context-sensitive decisions that weighed practical benefits against ecological risks. Student responses showed a clear gradation across performance levels, ranging from the comprehensive, multi-source reasoning of 'Excellent' students to the singular, mechanistically shallow explanations of those in the 'Needs Improvement' group. This variation provides strong qualitative evidence that the CT-HOT in Bio innovation successfully scaffolded students toward higher-order thinking outcomes. However, a smaller subgroup (20%) still requires targeted pedagogical support to strengthen their depth of analysis and contextual reasoning.

The strong performance of the majority of students (80% at Good or Excellent levels) lends empirical support to the growing body of literature advocating for the embedding of biological content within authentic social and ecological contexts. The instructional

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design, which situated asexual reproduction within the real-world problem of invasive species management, aligns with Thoman et al. (2025) and Busch et al. (2026), who argue that contextualizing biology instruction within social issues enhances student engagement and positions science as a tool for addressing societal challenges. A high proportion of students successfully connected reproductive mechanisms to ecological, agricultural, and economic impacts, rather than treating asexual reproduction as an isolated factual topic. This finding corroborates Sadler et al. (2016) and Young et al. (2023), who demonstrated that critical engagement with science–society interconnections are positively associated with content mastery. This suggests that the CT-HOT in Bio innovation did not merely transmit content about asexual reproduction but successfully cultivated the socially situated reasoning that Lin et al. (2023) identify as a core competency (Action, Literacy, Problem-solving) that biology curricula worldwide are increasingly expected to develop.

Students who reached the Excellent level demonstrated the capacity to extend beyond guided instruction, integrating multiple sources and independently generated hypotheses, whereas students at lower performance levels appeared to remain reliant on minimally scaffolded starting points (e.g., a single tool, a single citation). This pattern reinforces the pedagogical rationale underlying the Scaffolding Questions embedded within CT-HOT in Bio: by structuring guided-inquiry prompts at each of the four P-I-A-C stages, the innovation appears to have created the "assisted performance" conditions described by Chaiklin (2003) and van de Pol et al. (2010), enabling a majority of learners to internalize and independently apply the critical thinking process. The remaining 20% of students, who displayed only fragmented mechanistic understanding and singular-source reasoning, may represent learners whose zone of proximal development requires more intensive or individualized scaffolding than the current instructional design provided—an interpretation that points toward a concrete area for iterative refinement in future implementation cycles.

Student performance was evaluated across four dimensions: Problem Identification, Investigation, Analysis, and Conclusion/Evaluation. This structure mirrors and empirically validates the P–I–A–C framework, which was synthesized from Watson and Glaser (1980), Paul (1993), and Nekmanurak (1994). Notably, the qualitative differences observed between performance levels closely track the sub-competencies these frameworks specify: Excellent-level students exhibited the "assumption recognition" and "evaluation of arguments" described by Watson and Glaser, as well as the attention to "implications and consequences" emphasized by Paul (1993), through their explicit weighing of ecological risks (e.g., the potential for introduced predators to become new invasive threats). In contrast, Needs Improvement-level students' failure to compare alternative control methods or anticipate secondary ecological consequences reflects precisely the deficiencies these frameworks associate with lower-order or incomplete critical thinking.

Furthermore, 65% of the students performed at the "Excellent" level, demonstrating the ability to cite multiple evidence sources, weigh multifaceted advantages and disadvantages to justify decisions, and draw well-reasoned conclusions. This achievement corresponds closely to the Level 9 proficiency descriptors specified for Grade 10–12 students under Thailand's CBE framework (Office of the Education Council, 2021) for Core Competency 2 (Thinking Ability). This alignment suggests that the CT-HOT in Bio innovation is not only theoretically grounded but also practically effective in moving a substantial majority of students toward the specific national proficiency benchmarks intended for this age group.

Likewise, Wongsila and Yuenyong (2019) demonstrated that genetics content, when structured around ethically and socially significant decision-making tasks, effectively promoted both critical thinking and problem-solving abilities. The convergence of the present findings with prior research reinforces a key proposition: critical thinking is rarely

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an incidental byproduct of standard content delivery. Instead, it is most robustly developed through structured decision-making tasks that require students to weigh scientific evidence against practical, ecological, and ethical considerations. This principle formed the foundational design logic of the CT-HOT in Bio innovation, which required students to evaluate an invasive species scenario to recommend and justify a population control strategy.

The primary weaknesses observed among these students were their reliance on single sources, their failure to link biological mechanisms to ecological impacts, and an inability to evaluate comparative solutions. This pattern suggests that these students may still be operating at the 'knowledge' level of critical thinking rather than advancing to integrated 'skill' application (Watson & Glaser, 1980). This finding is consistent with the broader literature's caution (e.g., Thoman et al., 2025) that without deliberate and sustained scaffolding, socially contextualized content alone is insufficient to guarantee higher-order thinking gains for all learners. Consequently, the results support the researcher's recommendation that supplementary, individualized scaffolding activities be designed for this subgroup, potentially through more granular Scaffolding Questions or peer-assisted learning structures that more precisely target their specific zone of proximal development.

Taken together, these findings affirm that the revised CT-HOT in Bio instructional innovation, implemented during the R3 phase of the 2025 academic year, produced substantial gains in critical thinking competency among Grade 12 students, with the majority reaching Excellent or Good levels of performance. The results provide converging empirical support for socio-scientific issue-based instruction, Vygotskian scaffolding theory, and the P-I-A-C critical thinking framework, while also identifying a specific subgroup of learners for whom further pedagogical refinement is warranted. These findings contribute to the broader international and national discourse on competency-based biology education by demonstrating a concrete, replicable instructional model capable of systematically cultivating critical thinking within an authentic, ecologically relevant biological topic.

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