The Urgency of STEM-Integrated Project-Based Biology Learning to Enhance Students' Critical Thinking Skills: A Framework Synthesis for Secondary Education

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Abstract
In many secondary classrooms, biology is still taught as a sequence of concepts to be memorized rather than as a living science for interpreting evidence, solving problems, and making responsible decisions. Meanwhile, education systems increasingly demand that learners develop critical thinking—interpreting information, analyzing claims, evaluating evidence, inferring conclusions, and reflecting on reasoning quality—skills strongly associated with scientific literacy. Project-Based Learning (PjBL) and integrated STEM education provide complementary pathways to develop these competencies. PjBL organizes instruction around an authentic driving question and a sustained inquiry process culminating in a public product, while integrated STEM positions science and mathematics as anchor disciplines and uses engineering design and technology as connective practices. This article synthesizes research evidence and theory up to 2024 to argue for the urgency of STEM-integrated PjBL in biology learning as an instructional strategy to improve students' critical thinking. Using a framework-synthesis method, we integrate (1) critical thinking constructs (Delphi consensus and related frameworks), (2) empirical and meta-analytic evidence on PjBL and STEM in science learning, and (3) biology-specific affordances (systems, modeling, and socioscientific issues). Results are presented as an explanatory model linking STEM-PjBL design features to learning mechanisms and critical thinking outcomes, an evidence map, a practical project design template, and an assessment blueprint. The synthesis indicates that PjBL can promote critical thinking compared with traditional instruction, and that STEM-integrated variants add value by increasing the need for data-based reasoning, quantitative modeling, optimization, and design justification. We conclude with implementation guidance for teachers and school leaders, including scaffolding strategies, equity safeguards, and documentation approaches for credible reporting of learning outcomes.

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Keywords: biology education; STEM education; project-based learning; critical thinking; engineering design; scientific literacy; secondary school; assessment; 21st-century skills

1. Introduction

Biology education sits at a strategic intersection of science and life. Topics such as ecosystems, biodiversity, infectious disease, genetics, biotechnology, and human physiology are directly connected to real-world decisions that adolescents encounter through media, community debates, and everyday experiences. Yet, despite this relevance, secondary biology instruction often remains dominated by teacher-centered explanations and short-answer recall assessments. Such approaches may help students remember terminology, but they frequently fail to cultivate reasoning skills needed to evaluate evidence, justify claims, and solve complex problems.

Critical thinking is widely recognized as a core educational goal. The Delphi consensus report defines critical thinking as purposeful, self-regulatory judgment that results in interpretation, analysis, evaluation, and inference, as well as explanation of the evidential, conceptual, methodological, or contextual considerations upon which judgment is based (Facione, 1990) [5]. In science education, these skills translate into interpreting data, modeling causal relationships, evaluating claims, and revising conclusions under uncertainty—competencies that align with scientific literacy and responsible citizenship.

At the same time, STEM education has become a major educational agenda because it supports learners' ability to integrate scientific and mathematical ideas with technology and engineering design to address authentic problems. Kelley and Knowles (2016) [7] propose an integrated STEM framework in which mathematics and science serve as anchor disciplines, while engineering design provides coherence by connecting knowledge to problem solving through iterative design, testing, and optimization. Biology offers natural contexts for integrated STEM: bio-inspired design, environmental monitoring, biotechnology, and human health innovations.

Project-Based Learning (PjBL) provides a pedagogical structure that can make this integration teachable. PjBL is typically characterized by a driving question, sustained inquiry, learner autonomy with guidance, collaboration, and the creation of a tangible product shared with an audience. These features can create repeated opportunities for students to practice critical thinking in authentic contexts—especially when projects require measurement, modeling, design decisions, and evidence-based justification.

This article argues that STEM-integrated PjBL in biology is urgent because it addresses three converging needs: (1) strengthening students' critical thinking skills, (2) making biology learning relevant to real sustainability, health, and technology challenges, and (3) aligning secondary science education with 21st-century competencies and assessment reforms. The paper provides a framework synthesis of research up to 2024, translating evidence into practical guidance for classroom implementation and assessment.

2. Literature Review

This literature review integrates four strands: critical thinking theory and measurement, evidence on project-based learning (PjBL) and critical thinking outcomes, integrated STEM frameworks and evidence, and biology-specific learning design considerations.

Critical thinking constructs provide the conceptual target. The Delphi consensus emphasizes a combination of cognitive skills (interpretation, analysis, evaluation, inference, explanation, and self-regulation) and dispositions (e.g., inquisitiveness, fairness, and willingness to reconsider) that support high-quality judgment (Facione, 1990) [5]. For classroom design, this implies that instruction should not only present scientific facts, but also require students to justify claims using evidence, consider alternative explanations, and revise reasoning through reflection and feedback.

The project-based learning literature indicates that PjBL can support higher-order thinking when projects are well designed. Meta-analytic and review studies in science education report that project-based learning tends to improve learning outcomes compared with traditional instruction, with outcomes moderated by education level, task design, and comparative learning strategies. A meta-analysis in an Indonesian context (Tafakur, 2023) [9] concludes that PjBL promotes students' critical thinking skills and is generally superior to traditional learning across levels, though moderators matter. Broader meta-analyses and reviews (Balemen & Özer Keskin, 2018; Chen & Yang, 2019) [3, 4] similarly find positive effects of PjBL in science education, while emphasizing the need for scaffolds, teacher facilitation, and aligned assessment.

Integrated STEM education frameworks clarify how STEM integration can deepen reasoning demands. Kelley and Knowles (2016) [7] argue that integrated STEM requires meaningful connections across disciplines, typically through engineering design challenges, while keeping mathematics and science epistemically central. Integration is not merely adding a technology tool to a science lesson; it structures learning so that students must coordinate scientific concepts, quantitative reasoning, design constraints, and evidence to justify solutions. Such coordination is closely related to critical thinking: students must analyze data, evaluate trade-offs, infer implications, and explain design decisions.

Biology offers unique affordances for STEM-PjBL. Many biology topics are systems-oriented (e.g., feedback loops in ecosystems or homeostasis), data-rich (e.g., sampling and genetics), and connected to socio-ethical issues (e.g., biotechnology, conservation). These features make biology a strong domain for projects integrating scientific investigation with engineering design and technology-enabled data collection. Empirical studies support feasibility. For example, Novitasari, Isnaini, and Supriyadi (2024) [8] report that STEM-based PjBL significantly improves students' critical thinking in biology learning. Development research on STEM-PjBL worksheets for the human excretory system also reports high learning gains and feasibility outcomes (Indranuddin *et al*., 2024) [6].

The literature also warns about pitfalls. Projects can become product-oriented activities with limited reasoning impact if they emphasize completion without explicit evidence standards, argumentation, and reflection. STEM integration can become superficial if engineering design is treated as decoration rather than a reasoning practice involving criteria, constraints, testing, and optimization. Therefore, urgency must be paired with design principles and assessment tools that protect rigor and equity.

3. Method

This paper uses a framework synthesis approach to develop an evidence-informed argument and practical design guidance. Rather than conducting new experiments, we synthesize theoretical and empirical sources published up to 2024. The synthesis is designed to be useful for secondary biology teachers, curriculum developers, and school leaders seeking to justify and implement STEM-integrated PjBL to improve students' critical thinking.

Search and inclusion logic. We selected sources that (a) define or operationalize critical thinking (e.g., Delphi consensus), (b) provide empirical or meta-analytic evidence on PjBL and/or STEM approaches related to critical thinking or higher-order thinking in science learning, (c) provide integrated STEM education frameworks, and (d) include biology-specific applications when available. We prioritized peer-reviewed journal articles and reputable reports and restricted references to publications no later than 2024.

Analytic framework. Evidence was organized into four layers: (1) learning outcomes (critical thinking skills and dispositions), (2) pedagogical design features (PjBL and STEM integration), (3) learning mechanisms (systems reasoning, evidence use, argumentation, metacognition), and (4) assessment and implementation (rubrics, performance tasks, and continuous improvement cycles). The output is a set of conceptual models, evidence maps, and practical templates.

4. Results and Discussion

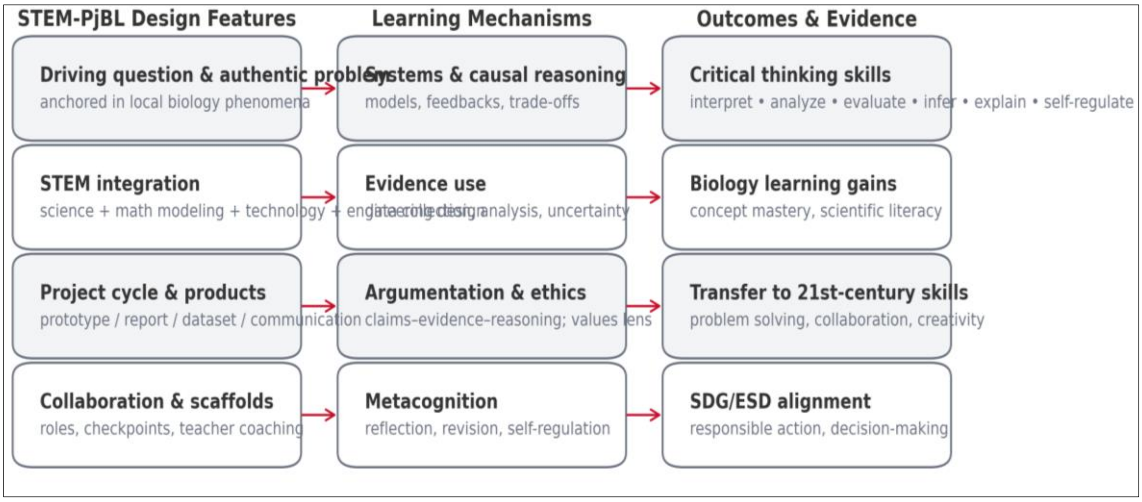

Fig 1: STEM-integrated PjBL biology learning framework for critical thinking

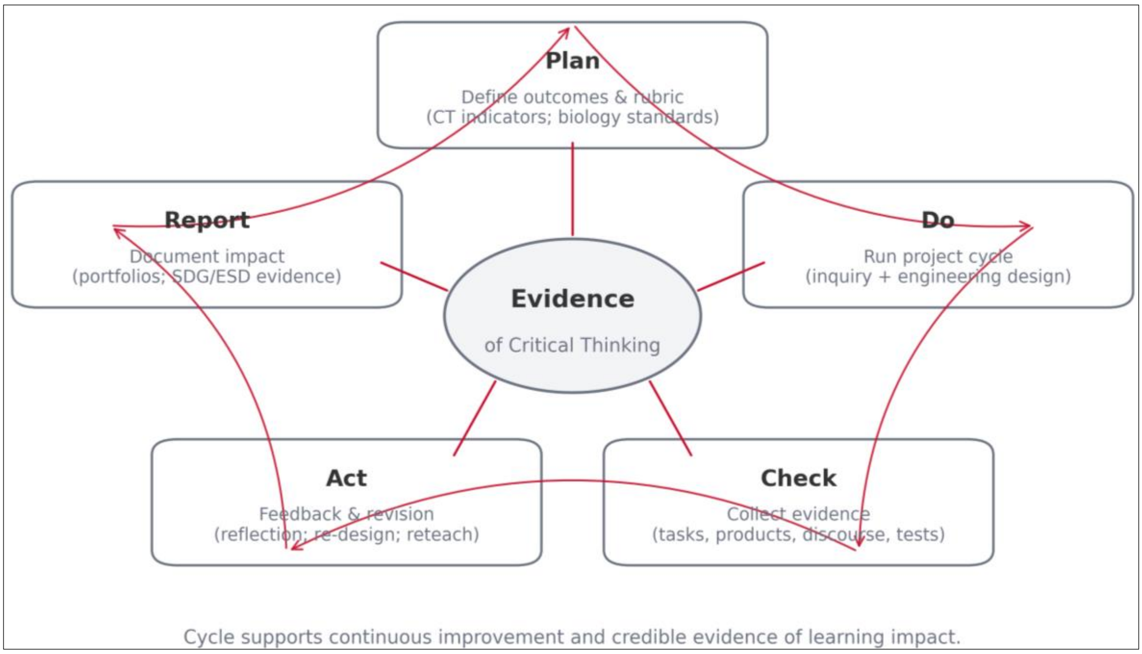

Fig 2: PDCA-aligned assessment cycle for critical thinking in STEM-PjBL biology

The synthesis yields four main results. First, we propose a conceptual framework (Figure 1) that explains how STEM-integrated PjBL design features can produce critical thinking gains through specific learning mechanisms. Second, we provide an evidence map (Table 1) summarizing representative findings from meta-analyses, framework papers, and biology-specific studies up to 2024. Third, we translate insights into a practical project design template for biology (Table 2), including STEM integration cues and critical thinking prompts. Fourth, we provide an assessment blueprint and improvement cycle (Figure 2 and Table 3) to help teachers generate credible evidence of critical thinking growth and refine instruction over time.

Result 1: Why STEM-PjBL is urgent for critical thinking in biology. Biology involves complex causal systems, uncertainty, and ethical trade-offs. Traditional instruction may describe these complexities, but students rarely practice reasoning with them. STEM-PjBL changes the epistemic demands of learning: students must define problems, gather or generate data, use mathematical reasoning, design and test solutions, and justify decisions with evidence. These activities align with critical thinking indicators such as analysis, evaluation, inference, explanation, and self-regulation (Facione, 1990) [5].

Result 2: Evidence from studies and syntheses. Meta-analytic evidence suggests that PjBL supports critical thinking compared with other approaches. Tafakur's (2023) [9] meta-analysis reports that PjBL promotes critical thinking, with effects moderated by education level and comparison strategy. Other meta-analyses (Balemen & Özer Keskin, 2018; Chen & Yang, 2019) [3, 4] report positive effects of PjBL in science education and emphasize implementation quality. Biology-specific studies strengthen the urgency argument: Novitasari *a*. (2024) [8] find that STEM-based PjBL improves students' critical thinking in biology, and Indranuddin *et al*. (2024) [6] report high gains and feasibility for STEM-PjBL worksheets in human physiology.

Result 3: Design principles for effective STEM-PjBL in biology. Effective projects include: (a) a driving question connected to authentic biological phenomena, (b) explicit learning goals and rubrics for critical thinking, (c) sustained inquiry with checkpoints, (d) meaningful STEM integration through modeling and engineering design constraints, (e) opportunities for argumentation and peer critique, and (f) structured reflection and revision. Without these, projects risk becoming hands-on activities with limited reasoning impact.

Result 4: Assessment and credible evidence. Figure 2 proposes an assessment cycle aligned to Plan–Do–Check–Act and reporting. Teachers can combine multiple evidence sources: (1) pre/post critical thinking tests (essay or scenario-based), (2) performance tasks such as causal loop diagrams or data analysis memos, (3) project artifacts (prototype, dataset, report), and (4) reflective self-regulation logs. The cycle supports continuous improvement and documentation for accountability and communication.

Implications for equity and feasibility. STEM-PjBL can widen gaps if projects assume access to technology or outside resources. To prevent this, teachers should provide in-class access to materials, use low-cost sensors or shared devices, scaffold roles so that all students practice reasoning tasks, and evaluate learning based on evidence and thinking rather than on product aesthetics. Inclusive grouping, language supports, and flexible demonstration formats (oral defense, infographic, written report) can also improve equity.

Table 1: Evidence map: representative sources linking PjBL/STEM and critical thinking (≤ 2024).

Source	Context & level	Design / type	Key finding related to critical thinking	Notes for biology STEM-PjBL design
Facione (1990) [5]	General education	Delphi consensus report	Defines critical thinking skills and dispositions for assessment and instruction.	Use CT indicators (interpret, analyze, evaluate, infer, explain, self-regulate) for rubrics and tasks.
Kelley & Knowles (2016) [7]	STEM education	Conceptual framework paper	Integrated STEM: science & math as anchors; engineering design connects disciplines; authentic problems.	Use engineering design (criteria/constraints, testing, optimization) to deepen reasoning in biology projects.
Balemen & Özer Keskin (2018) [3]	Science education	Meta-analysis	Project-based learning shows positive effects in science education (moderated by design/context).	Emphasize scaffolding, teacher facilitation, and aligned assessment to ensure "minds-on" learning.
Chen & Yang (2019) [4]	Mixed disciplines	Meta-analysis	PBL effects on achievement vary; moderators include discipline and implementation features.	Plan explicit supports and checkpoints; avoid treating projects as unstructured group work.
Anazifa & Djukri (2017) [2]	Science education (Indonesia)	Quasi-experimental	PjBL and PBL improve thinking skills compared to conventional learning in science contexts.	Adopt inquiry scaffolds and reflection; use biology phenomena as driving contexts.
Tafakur (2023) [9]	Multi-level education	Meta-analysis (29 studies)	PjBL promotes students' critical thinking; moderated by education level and comparison strategy.	Combine PjBL with STEM integration to strengthen evidence use and design justification.
Novitasari *et al.* (2024)] [8]	Secondary biology	Quasi-experimental	STEM-based PjBL significantly improves students' critical thinking.	Use biology topics and essay/scenario CT tests; ensure authentic problem framing.
Indranuddin *et al.* (2024) [6]	Secondary biology	R&D + effectiveness	STEM-PjBL worksheets show high gains and feasibility; improve critical thinking.	Provide structured worksheets and checkpoints; integrate data and modeling tasks.
Afriana *et al.* (2016) [1]	Science education	Empirical study	STEM-integrated PjBL improves science literacy; gender considerations reported.	Plan equitable participation; distribute roles; support communication and reasoning for all students.

Table 2: Biology STEM-PjBL project design template to elicit critical thinking.

Project phase	Teacher moves	Student critical thinking actions	STEM integration cues	Evidence / assessment
Launch (Driving question)	Present authentic phenomenon; clarify criteria; co-define success	Interpret context; ask questions; define problem boundaries	Use data/story + constraints (time, cost, safety)	Entry ticket; initial concept map; problem statement rubric
Inquiry & research	Provide mini-lessons; scaffold data quality; model CER reasoning	Analyze sources; evaluate credibility; plan investigation	Select tools/sensors; plan variables; math for sampling	Research log; source evaluation; investigation plan
Design & build	Coach engineering design cycle; require justification of choices	Infer design options; evaluate trade-offs; explain decisions	Prototype (e.g., biofilter, mini-greenhouse, fermentation setup)	Design brief; decision matrix; peer critique notes
Test & iterate	Set testing protocols; prompt error analysis and revision	Analyze data; evaluate performance; self-regulate revisions	Graphing; optimization; quality control	Dataset + analysis memo; iteration log; rubric
Communicate & reflect	Facilitate public sharing; guide reflection on evidence and ethics	Explain conclusions; justify claims; reflect on learning process	Digital communication; visualization; community feedback	Final report; presentation defense; reflection essay

Table 3: Critical thinking rubric (adapted from Facione, 1990) [5] for biology STEM-PjBL performance tasks.

CT skill	Emerging	Developing	Proficient	Advanced
Interpretation	Restates information with major gaps	Identifies basic meaning; limited context	Accurately interprets data and context	Interprets nuanced patterns; links context and assumptions
Analysis	Lists facts without relationships	Identifies some relationships; incomplete	Analyzes causal links and mechanisms	Builds multi-factor models; considers feedbacks and confounders
Evaluation	Accepts claims without criteria	Uses simple criteria; inconsistent	Evaluates evidence quality and limitations	Critically compares alternatives; judges robustness under uncertainty
Inference	Conclusions not supported by evidence	Partially supported; misses alternatives	Draws warranted conclusions; notes uncertainty	Infers implications; proposes testable next steps and alternatives
Explanation	Explains with vague statements	Explains with some evidence; limited logic	Explains with coherent claim–evidence–reasoning	Explains to different audiences; anticipates counterarguments
Self-regulation	No reflection or revision	Limited reflection; superficial edits	Reflects and revises using feedback and evidence	Iteratively improves reasoning; monitors bias and decision quality

5. Conclusion

This framework synthesis argues that STEM-integrated project-based biology learning is urgent for improving students' critical thinking skills. The urgency is grounded in biology's systems- and evidence-oriented nature, the educational demand for critical thinking, and research evidence indicating that PjBL and STEM-oriented approaches can promote higher-order thinking when well designed. Biology-specific studies up to 2024 further indicate feasibility and positive impacts.

For practice, the paper provides conceptual models (Figures 1–2) and practical templates (Tables 1–3) that help teachers align projects with critical thinking indicators, build meaningful STEM integration, and collect credible evidence of learning impact. Future empirical work should examine long-term transfer, scalability across diverse school contexts, and the interaction between teacher professional development and STEM-PjBL implementation quality.

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