International Journal of Education and Teaching Zone
Volume 5, Issue 1, 2026, pp. 109-128

https://doi.org/10.57092/ijetz.v5i1.548
IJETZ
p-ISSN: 2963-7899 | e-ISSN: 2830-7925

Original Article

Design and Validation of Canvas-Based Interactive General Biology Modules: Scientific Literacy Scaffolds within Project-Based Learning to Support 4C Skills

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Abstract: The Society 5.0 era calls for learning innovations that support both content understanding and 21st-century competencies, particularly the 4C skills (communication, collaboration, critical thinking, and creativity). This study designed and validated Canvas-based interactive General Biology modules by embedding scientific literacy scaffolds within Project-Based Learning (PjBL) phases to support students' 4C-related skills. The development followed Plomp's model (preliminary research, prototyping, and assessment) and involved 25 purposively selected students at STKIP Muhammadiyah Sungai Penuh. The integration mechanism was operationalized by mapping scientific literacy components (e.g., interpreting scientific information, evaluating evidence, and scientific reasoning) into each PjBL phase and implementing them through Canvas features such as structured Modules, staged Assignments, Rubrics, Discussions/Groups, and feedback tools. Data were collected using validity and practicality questionnaires, checklists, and interviews. Results indicated that the modules met the criteria for validity (mean score 87.55, valid) and practicality based on lecturer and student responses (scores 84.25 and 84.89, practical). A limited tryout produced N-Gain indicators suggesting promising 4C-related improvement (communication 0.75, collaboration 0.75, critical thinking 0.78, creativity 0.74), but generalizability is limited due to the small, single-institution sample.

Keywords :
Integrated pedagogical design; Technology-enhanced project-based learning (TE-PjBL); Scientific literacy scaffolding; Canvas LMS; 4 Skills

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Article History:
Received 1 November 2025; Revised 16 Janury 2026; Accepted 16 February 2026
Available online 28 February 2026

INTRODUCTION

The paradigm shift in the Society 5.0 era demands learning innovations that go beyond knowledge transmission to explicitly develop 21st-century competencies, particularly the 4C skills: creative thinking, critical thinking, communication, and collaboration (Trilling & Fadel, 2009; Van Laar *et al*., 2017). In higher education, this requires students to solve authentic problems, collaborate effectively, and engage meaningfully with digital technologies. In science education, General Biology plays a strategic role by providing foundational concepts while fostering evidence-based reasoning in real-world contexts (Choi *et al*., 2020). Recent studies show increasing use of technology in biology education to enhance interaction, contextualize concepts, and strengthen science-related skills (Almendingen *et al*., 2021). However, digital media is often used in general terms, without coherent integration of pedagogy, scientific literacy, and assessment. Observations indicate persistent challenges: traditional materials dominate, limiting active interaction, application of concepts, creative thinking, and collaboration. These issues converge on the lack of a structured, interactive, project-based teaching framework that scaffolds inquiry, builds scientific literacy, and promotes collaboration. Therefore, the needed innovation is validated interactive modules embedding scientific literacy scaffolds within Project-Based Learning to support students' 4C-related skills.

Project-Based Learning (PjBL) fosters creative thinking and collaboration through authentic projects (Bell, 2010; Guo *et al*., 2020; Yuliati & Saputra, 2020), while LMS Canvas supports interaction and engagement through various features (Chen *et al*., 2021; Peacock *et al*., 2020; Soh & Tan, 2023). However, existing studies treat these components separately. Validated interactive materials for General Biology that integrate Canvas-supported PjBL with explicit scientific literacy scaffolds to support 4C skills remain limited the focus of this study. Scientific literacy strengthens understanding of scientific concepts and their application in real-life contexts, including reasoning and evidence-based decision making (Bybee, 2013; OECD, 2019; Vieira & Tenreiro-Vieira, 2016). Embedding scientific literacy within innovative models can enhance higher-order thinking and align learning with 21st-century demands (Lai & Viering, 2012; Nugraha *et al*., 2017).

Research on PjBL supported by digital technology highlights the potential of LMS like Canvas in organizing learning and facilitating interaction (Liu *et al*., 2023), though empirical work in higher-education General Biology remains limited (Aksela & Haatainen, 2019; Chen & Yang, 2019). These findings reveal a synthesis gap: the literature lacks a validated, unified instructional design integrating PjBL phases, scientific literacy scaffolds, and LMS functionality into interactive materials structured to support students' 4C skills in General Biology. Bibliometric mapping shows strong co-occurrence between PjBL and 4C-related terms, indicating growing research interest; however, studies operationalizing scientific literacy scaffolds within LMS-supported PjBL for General Biology remain limited.

This gap suggests that existing studies tend to examine PjBL implementation, digital platforms, or 4C skill development in isolation rather than as an integrated pedagogical ecosystem. Consequently, there is limited empirical evidence on how specific LMS features such as structured discussion forums, embedded formative assessments, collaborative workspaces, and analytics can be deliberately aligned with PjBL stages (problem orientation, project design, investigation, product creation, and reflection) while simultaneously embedding scientific literacy components. Addressing this integrative dimension is essential to move beyond descriptive implementation studies toward a validated instructional framework that systematically supports higher-order thinking and transferable 4C competencies in General Biology contexts.

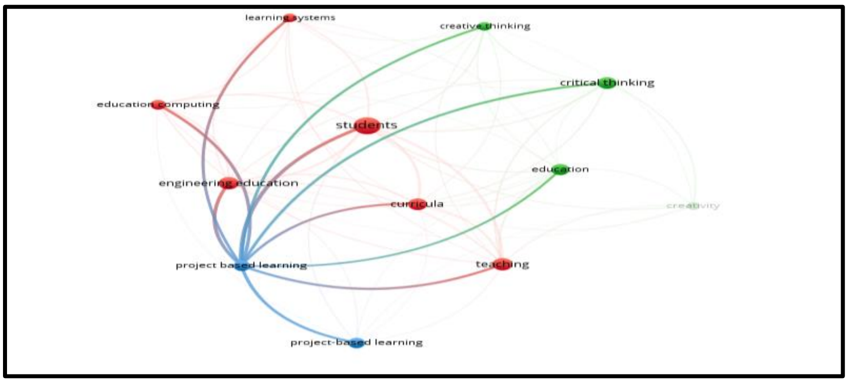

Figure 1. Relationship between Project-Based Learning and Critical and Creative Thinking Skills

Figure 1. illustrates the interrelationships between Project-Based Learning (PjBL) and the development of students' critical and creative thinking skills. The network visualization highlights that PjBL serves as a central pedagogical approach, strongly connecting with curricular content, teaching strategies, and learning systems, while simultaneously linking to students' engagement and the enhancement of critical and creative thinking competencies. The thicker and darker edges indicate stronger associations, suggesting that implementing structured PjBL activities can significantly influence both cognitive processes and practical application of knowledge in authentic contexts. This figure underscores the role of PjBL not only in knowledge acquisition but also in fostering higher-order thinking skills, supporting previous findings that experiential, project-driven learning promotes creativity, critical reasoning, and collaborative problem-solving (Bell, 2010; Thomas, 2000; Hmelo-Silver, 2004). The relationship between project-based learning and collaborative and communication skills can be shown in Figure 2.

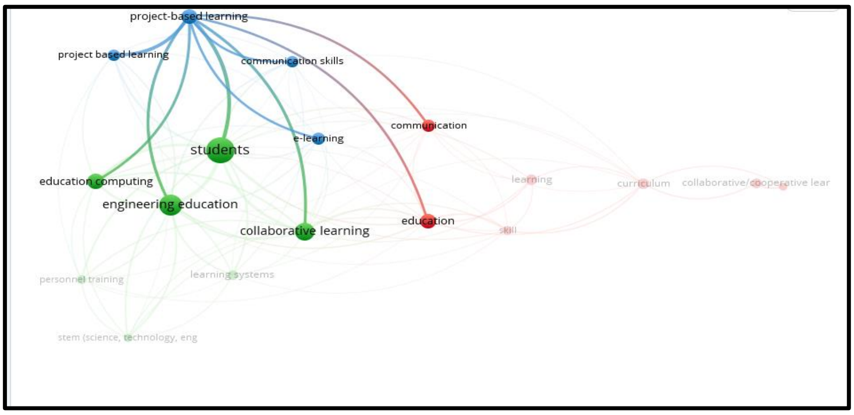

Figure 2. Relationship between Project-Based Learning and Collaborative and Communication Skills

According to previous research, project-based learning (PjBL) has been shown to enhance students' communication and collaboration skills within the context of engineering and science education (Thomas, 2000). As illustrated in Figure 2, there is a strong relationship among project-based learning, collaborative learning, and communication skills, indicating that the implementation of PjBL fosters active student engagement as well as peer-to-peer interaction to achieve learning objectives (Bell, 2010). Therefore, integrating PjBL into the curriculum not only strengthens academic content mastery but also cultivates essential soft skills that contribute to students' professional readiness (Hmelo-Silver, 2004). If desired, a more detailed version could be developed to address the relationships between additional nodes in Figure 2, such as students, engineering education, and learning systems, thereby providing a more comprehensive visual and analytical interpretation.

The urgent need in General Biology education is for interactive learning materials that go beyond digital presentation to structured modules integrating scientific literacy scaffolds within PjBL activities (Choi *et al*., 2020; Trilling & Fadel, 2009; Van Laar *et al*., 2017). Such materials guide students through collaborative projects, applying concepts to contextual problems and refining understanding via evidence-based reasoning, thereby fostering active engagement and 4C skills, especially creativity and collaboration (Bell, 2010; Thomas, 2000). The study's novelty lies in providing a validated pedagogical mechanism that operationalizes PjBL phases within Canvas, embedding scientific literacy components interpreting information, evaluating evidence, and scientific reasoning into structured learning sequences (Modules, staged Assignments, rubric-based assessment, Discussions/Groups, and feedback tools) (Hmelo-Silver, 2004; Kokotsaki *et al*., 2016). Following Plomp's development model, this research emphasizes validity and practicality while exploring the potential for 4C skill enhancement through limited implementation, producing a prototype and instructional framework that can guide lecturers and inform broader effectiveness testing (Henderson *et al*., 2017; Jonassen, 2011).

METHOD

This study employed a development research approach based on the Plomp model to design and produce a Canvas-based interactive General Biology module that integrates scientific literacy scaffolds within Project-Based Learning (PjBL) phases, aiming to support students' 4C-related learning processes (Creemers & Kyriakides, 2008; Plomp, 2013; Thomas, 2000). Consistent with the principles of development research, the primary focus was on the quality of the product, particularly its validity and practicality, which were evaluated through formative assessment (Richey & Klein, 2007; van den Akker, 2013). Additionally, a limited one-group pretest–posttest design was conducted solely to explore potential indicators of learning gains during prototype use; therefore, the results were not interpreted as evidence of causal relationships or generalizable effectiveness (Fraenkel *et al*., 2019; Shadish *et al*., 2002). The study was conducted at STKIP Muhammadiyah Sungai Penuh during the 2025/2026 academic year. Participants consisted of 25 students enrolled in the General Biology course, selected through purposive sampling for a limited tryout. Although this sample size and single-institution context were appropriate for prototype refinement and practicality evaluation, they were not sufficient for broad generalization. As for the development process in the research that has been carried out, it is illustrated in Figure 3, which follows three main phases.

The first phase, the Preliminary Research Phase, aimed to identify learning problems and design requirements through interviews and review of existing course materials and learning implementation. The findings were translated into design specifications, including structuring the Project-Based Learning (PjBL) phases into coherent learning sequences and embedding scientific literacy scaffolds such as interpreting scientific information, evaluating evidence, and engaging in scientific reasoning across project milestones within the module. The second phase, the Prototyping Phase, involved designing and implementing a prototype in Canvas, which was iteratively refined through formative evaluation steps, including self-evaluation, expert review (for validity testing), one-to-one evaluation, and small group trials. Feedback from each step was used to improve module content, learning flow, scaffolding prompts, and usability. The final phase, the Assessment Phase, consisted of a formative tryout and practicality test. In this phase, the revised prototype was implemented in a limited setting to evaluate practicality in terms of ease of use, time efficiency, and perceived benefits for learning activities. During this implementation, a pretest–posttest was administered to explore potential trends in students' 4C-related performance when using the developed module, although the results were not intended to indicate causal effects.

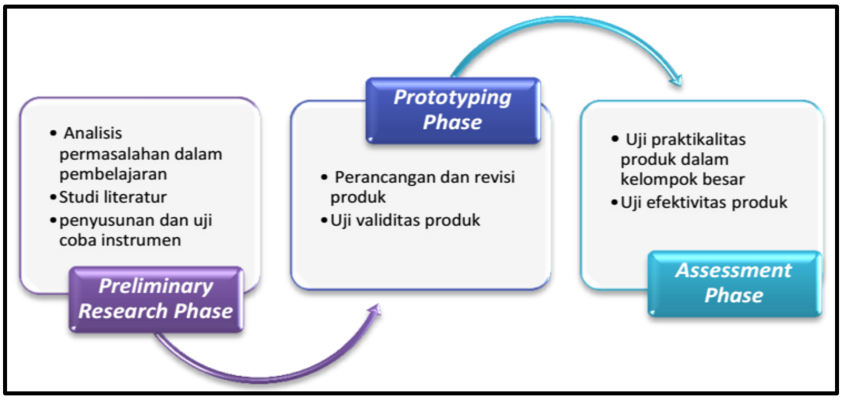

Figure 3. Stages of Product Development

Figure 3 illustrates the stages of product development for the Canvas-based interactive General Biology module. The process begins with the Preliminary Research Phase, which involves analyzing learning problems, reviewing relevant literature, and preparing and testing research instruments. Insights from this phase are then used in the Prototyping Phase, where the module is designed, implemented, and iteratively revised based on product validity testing. Finally, the Assessment Phase evaluates the practicality and effectiveness of the developed product through large-group trials and product performance testing. This structured, iterative approach ensures that the module is both pedagogically sound and practically feasible for supporting students' learning processes.

Data were collected using multiple instruments, including (1) interview guidelines during the preliminary phase, (2) a self-evaluation checklist, (3) expert validity questionnaires, (4) one-to-one evaluation questionnaires, (5) small-group trial questionnaires, and (6) lecturer and student practicality questionnaires. To examine the exploratory gains, students completed pretest and posttest tasks aligned with the 4C indicators, which were assessed using the same scoring rubric and procedures employed throughout the study. Qualitative data from interviews and open-ended responses were analyzed descriptively to guide product revisions, while quantitative data from the questionnaires were analyzed using descriptive statistics. All questionnaire responses were measured on a 4-point Likert scale to ensure consistency and reliability in scoring (Creswell & Creswell, 2018; Fraenkel *et al*., 2019).

To explore potential trends in student learning during the limited tryout, learning gains were estimated using the normalized gain (N-Gain), calculated from pretest and posttest scores (Hake, 1999). N-Gain values were interpreted according to standard criteria, with scores greater than 0.7 considered high, scores between 0.3 and 0.7 considered medium, and scores below 0.3 considered low. Given that this study did not include a comparison or control group and was conducted within a development research context, N-Gain results were reported solely as preliminary indicators of potential improvement rather than as evidence of causal effects or generalizable effectiveness (Creswell & Creswell, 2018; Fraenkel *et al*., 2019).

RESULT AND DISCUSSION

Validity of the Interactive General Biology Teaching Materials Assisted by LMS Canvas Integrated with Scientific Literacy and PjBL to Enhance 4C Skills

The validation data of the interactive General Biology teaching materials, designed to be delivered through the LMS Canvas and integrated with scientific literacy and Project-Based Learning (PjBL) principles, as assessed by expert validators, are presented in Table 1. This validation process is critical to ensure the instructional materials meet content accuracy, pedagogical effectiveness, and usability standards, aligning with established guidelines for educational material development (Branch, 2009; Richey *et al*., 2012). Expert evaluation provides systematic feedback that informs revisions, enhancing the materials' quality and their potential impact on students' conceptual understanding and scientific skills. The Validity Test Results of Interactive General Biology Teaching Materials Assisted by LMS Canvas Integrated Scientific Literacy and PjBL in this research can be seen in Table 1.

Table 1. Results of the Validity Test of Interactive General Biology Teaching Materials Assisted by LMS Canvas Integrated with Scientific Literacy and PjBL

No	Assessment Aspec	Validity Score (%)	Criteria
1	Content feasibility	88,88	Valid
2	Language	87,50	Valid
3	Presentation	86,36	Valid
4	Graphics	87,50	Valid
5	4C skills	87,50	Valid
	Average	87,55	Valid

Table 1 shows the results of the validity assessment of the interactive General Biology teaching materials developed for LMS Canvas, integrated with scientific literacy and Project-Based Learning (PjBL). Expert validators evaluated five aspects: content feasibility, language, presentation, graphics, and 4C skills (Critical thinking, Communication, Collaboration, Creativity). The scores ranged from 86.36% to 88.88%, with an overall average of 87.55%, indicating that all aspects were considered valid. Content feasibility received the highest score (88.88%), demonstrating alignment with curriculum objectives and accuracy of material. Language (87.50%) and presentation (86.36%) showed that the materials are clear, structured, and pedagogically appropriate. Graphics (87.50%) were assessed as effective and visually supportive of learning, while 4C skills (87.50%) indicated that the materials promote critical thinking, collaboration, communication, and creativity among students. Overall, these results confirm that the teaching materials are suitable for implementation, consistent with best practices in expert validation for interactive and student-centered instructional design (Branch, 2009; Richey *et al*., 2012). This score can be interpreted as evidence that the module does not merely state 4C as a goal, but translates it into task designs, performance indicators, and interactive learning activities that encourage evidence-based reasoning and contextual application central elements of scientific literacy (Bybee, 2013) and closely linked to the development of 21st-century competencies (Trilling & Fadel, 2009).

From the language aspect, the validators' valid judgment indicates that the module's wording does more than meet general academic language standards; it is sufficiently clear to operationalize the intended learning mechanism in a Canvas environment. In this module, language functions as an instructional guide that directs students through PjBL milestones and helps them respond to scientific literacy scaffolds (e.g., prompts to interpret information, justify decisions with evidence, and articulate reasoning). The validity score therefore suggests that students are likely able to follow project instructions, understand rubric expectations, and participate meaningfully in discussions and group coordination without being hindered by ambiguous phrasing. This interpretation is consistent with the view that strong linguistic structure supports motivation and comprehension (Sari, 2020). It also aligns with general guidance that teaching materials should use clear sentences, maintain coherence between sentences, and avoid unnecessarily complex or lengthy statements, which is particularly important when instructions are implemented as staged tasks in digital modules (Depdiknas, 2008; Prastowo, 2011).

The valid rating for the presentation aspect indicates that validators found the module's learning flow and organization coherent and implementable as a structured PjBL pathway. The module stages each project phase into clear activities, deliverables, milestones, task sequences, and assessment checkpoints within Canvas, ensuring students understand what to do, when, and how performance is assessed. This score confirms the clarity of PjBL-phase operationalization and its alignment with embedded scientific literacy scaffolds. While general standards emphasize clarity, sequencing, and completeness (Depdiknas, 2008), these findings support the view that systematic presentation aids understanding in complex tasks (Prastowo, 2011). Validator approval also suggests the module fosters active engagement, problem solving, and 4C skills critical thinking, creativity, and communication through structured project work (Kokotsaki *et al*., 2016; Thomas, 2000).

From the graphics aspect, the valid rating indicates that the visual layout and media elements were judged adequate to support usability, navigation, and attention within the Canvas-based module. This matters because the product's novelty is not simply that it is digital, but that it uses Canvas as a structured environment to deliver project milestones and literacy scaffolds; therefore, graphics and layout function pedagogically by helping students locate resources, understand task requirements, and engage with interactive checkpoints without disrupting the project flow. The validators' approval suggests that images and visual organization contribute to attractiveness and reduce fatigue while still supporting task completion (Prastowo, 2011). Canvas also enables interactive media elements such as embedded videos, animations, and quizzes, which can strengthen motivation (Al-Samarraie *et al*., 2018). However, within the logic of this study, the key point is that the validators considered these digital and visual elements sufficiently aligned with the module's integrated design supporting, rather than distracting from, the staged PjBL process and scientific literacy scaffolds intended to support students' 4C skills.

The "valid" rating for the 4C skills integration indicates that the Canvas-based module operationalizes these competencies through a coherent PjBL design supported by scientific literacy scaffolds, rather than merely listing them as outcomes. This is significant, as 4C skills are central to 21st-century education (Trilling & Fadel, 2009), and the validators' judgment suggests that the module's tasks, rubrics, and interaction patterns effectively align with these competencies. Specifically, critical thinking is embedded in evidence-based project decisions and issue analyses, creativity in ideation and project outputs, collaboration in structured group roles and coordinated deliverables, and communication in staged reporting and presentations. Validators' approval reflects recognition that Canvas tools functionally support these skills discussion spaces justify claims, group features manage collaboration, and rubric-based assessment clarifies performance expectations rather than serving as generic technology. This aligns with prior findings that PjBL supported by an LMS can foster 4C development (Kokotsaki *et al*., 2016) and, within this study, confirms that integrating scientific literacy scaffolds in PjBL via Canvas is clear and feasible rather than abstract.

Practicality of the Interactive General Biology Teaching Materials Assisted by LMS Canvas Integrated with Scientific Literacy and PjBL

The practicality of the interactive General Biology teaching materials developed for LMS Canvas and integrated with scientific literacy and Project-Based Learning (PjBL) was evaluated through feedback from lecturers and students who implemented the module in class. The assessment examined ease of use, clarity of instructions, usability of Canvas features, and alignment with PjBL phases and 4C skill development. The results, presented in Tables 2 and 3, indicate the module’s feasibility and user acceptance in authentic classroom settings, consistent with established principles of instructional design evaluation (Branch, 2009; Richey *et al*., 2012). The observations for lecturer-based practicality results are detailed in Table 2.

Table 2. Results of the Practicality Test of Interactive General Biology Teaching Materials Assisted by LMS Canvas Integrated with Scientific Literacy by Lecturers

No	**Assessment Aspect**	**Practically Score (%)**	**Criteria**
1	Ease of use	83,33	Practical
2	Efficiency of learning time	83,33	Practical
3	Benefits	86,36	Very Practical
	Average	84,25	Practical

Table 2 presents the results of the practicality test of the interactive General Biology teaching materials as assessed by lecturers. The module was evaluated across three aspects: ease of use, efficiency of learning time, and benefits. The scores ranged from 83.33% to 86.36%, with an overall average of 84.25%, indicating that the module is considered practical for classroom implementation. Specifically, ease of use and efficiency of learning time both scored 83.33%, showing that lecturers found the module user-friendly and suitable for effective time management during instruction. The benefits aspect received the highest score (86.36%), suggesting that the module effectively supports learning objectives and enhances students' engagement and understanding. These results demonstrate that the module is feasible and functional in practice, consistent with established criteria for evaluating the practicality of educational materials. As for the Results of the Practicality Test of Interactive General Biology Teaching Materials Assisted by LMS Canvas Integrated with Scientific Literacy by Students can be seen and observed in Table 3

Table 3. Results of the Practicality Test of Interactive General Biology Teaching Materials Assisted by LMS Canvas Integrated with Scientific Literacy by Students

No	**Assessment Aspect**	**Practically Score (%)**	**Criteria**
1	Ease of use	83,88	Practical
2	Efficiency of learning time	84,67	Practical
3	Benefits	86,14	Very Practical
	Average	84,89	Practical

Table 3 presents the results of the practicality test of the interactive General Biology teaching materials as assessed by students. The module was evaluated across three aspects: ease of use, efficiency of learning time, and benefits. Scores ranged from 83.88% to 86.14%, with an overall average of 84.89%, indicating that students found the module practical for learning. Ease of use (83.88%) and efficiency of learning time (84.67%) show that students were able to navigate the module comfortably and complete learning activities within a reasonable timeframe. The benefits aspect received the highest score (86.14%), reflecting that the module effectively supported understanding of content, engagement in learning, and application of scientific literacy. Overall, these findings suggest that the module is both feasible and effective in promoting student-centered learning, aligning with established standards for evaluating the practicality of instructional materials (Richey, Klein, & Nelson, 2012; Branch, 2009).

From the ease of use aspect, the practical rating suggests that users did not experience major barriers in understanding instructions, following the staged PjBL flow, or navigating the Canvas environment. Rather than attributing usability solely to "simple language," the results imply that the module's instructional components (task descriptions, milestone requirements, and rubrics) were sufficiently explicit to guide students through projects and literacy-focused prompts without excessive reliance on lecturer explanation. Such clarity and readability are essential characteristics of well-prepared learning materials (Majid, 2012) and align with the notion that practicality includes usability for both lecturers and students (Nieveen, 2013). In addition, the digital organization of content and activities in Canvas likely contributed to navigational clarity, consistent with findings that LMS integration can simplify instructions and support active engagement in biology learning (Tauhidah *et al*., 2021). At the same time, the difference between lecturer and student scores (if any) should be read substantively: lecturer practicality often reflects ease of setup and monitoring, whereas student practicality reflects ease of navigation and task completion two usability perspectives that may not always align (Nieveen, 2013).

From the efficiency of learning time aspect, the practical classification indicates that the module helped streamline learning processes during implementation. This efficiency is plausibly linked to the module structure in which scientific literacy tasks are embedded directly into project milestones, so students can engage in evidence-based reasoning at the moment it is needed (e.g., before submitting a project decision or report), rather than treating literacy activities as separate add-ons. Well-developed materials should allow students to revisit content and manage learning pace more independently (Prastowo, 2011), and time efficiency is a key indicator of practicality in development research because it reflects how streamlined the learning process becomes when the design is workable (Plomp & Nieveen, 2013). Moreover, Canvas features such as centralized resource access, submission portals, and organized task sequences can reduce administrative friction, allowing more time for essential learning activities (Lonn & Teasley, 2009). In this study, the practicality scores suggest that these platform affordances were not merely present, but functioned in support of the integrated PjBL scientific literacy workflow, enabling students to focus more on discussion, collaboration, and project completion.

The practicality findings confirm that the developed module is user-friendly and demonstrate that embedding scientific literacy scaffolds within PjBL phases via Canvas is feasible for classroom implementation. To further strengthen this interpretation, future refinements should report key qualitative feedback, such as which Canvas tools enhanced collaboration, which instructions were unclear, or which tasks were time-consuming, capturing both acceptance and design strengths (Nieveen, 2013; Plomp & Nieveen, 2013). In terms of benefits, both lecturers and students rated the module as very practical, with lecturers noting that it facilitated their role as facilitators and supported content explanation. The module not only delivers information but also promotes 21st-century 4C skills critical thinking, creativity, collaboration, and communication through scientific literacy and PjBL. Such beneficial teaching materials equip students with skills to face global challenges (OECD, 2019) and align with findings that interactive LMS-based materials enhance motivation, independence, and critical thinking (Rasheed *et al*., 2020).

Overall, the validity and practicality results indicate that the Canvas-based interactive General Biology modules, integrating scientific literacy scaffolds within PjBL phases, are suitable for implementation in the learning process. This finding addresses the gap in pedagogically coherent digital materials that unify LMS functionality with structured PjBL workflows and literacy supports (Branch, 2009; Richey *et al.*, 2012). The study's key contribution lies in validating the integration mechanism itself PjBL sequencing, literacy scaffolds, and Canvas-supported implementation demonstrating that the design is both academically sound and feasible for classroom use. However, while these findings confirm the module's usability and acceptability, they do not provide direct evidence of causal improvements in students' 4C skills. The results therefore provide a solid foundation for further research using broader samples and experimental or comparative designs to examine effectiveness (Trilling & Fadel, 2009; Thomas, 2000). The module interface is presented in Figure 4.

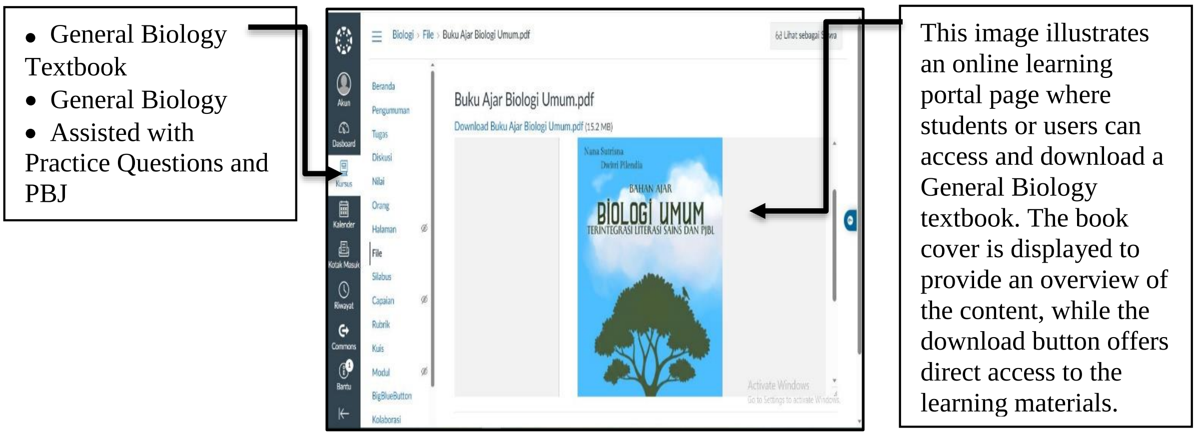

Figure 4. Canvas LMS Interface

Preliminary 4C Learning Gains from Canvas-Based Interactive General Biology Modules Integrating Scientific Literacy and PjBL

Data on the preliminary indicators of students' 4C-related skills during the limited implementation of the developed Canvas-based interactive General Biology modules, which embed scientific literacy scaffolds within Project-Based Learning (PjBL) phases, were collected through pretest and posttest questionnaires administered before and after the tryout period. These data provide initial evidence of the module's potential to foster critical thinking, creativity, collaboration, and communication in an authentic learning context. The results, summarized in Figure 5, illustrate changes in students' 4C-related competencies and offer insight into how the integration of PjBL phases and scientific literacy scaffolding can support and become a means of developing 21st-century skills in teaching General Biology. The data indicate measurable improvements in critical thinking, particularly in students' ability to analyze biological phenomena, interpret empirical evidence, and construct evidence-based arguments.

Creativity was reflected in the originality and feasibility of project outputs, as students designed solutions grounded in biological concepts. Communication skills developed through structured presentations, peer feedback sessions, and reflective discussions embedded within each PjBL phase. Collaboration was strengthened through clearly defined group roles, shared digital workspaces, and iterative problem-solving processes. Collectively, these findings suggest that the systematic alignment of project stages, literacy scaffolds, and instructional support mechanisms fosters a coherent learning environment conducive to sustainable 4C skill development.

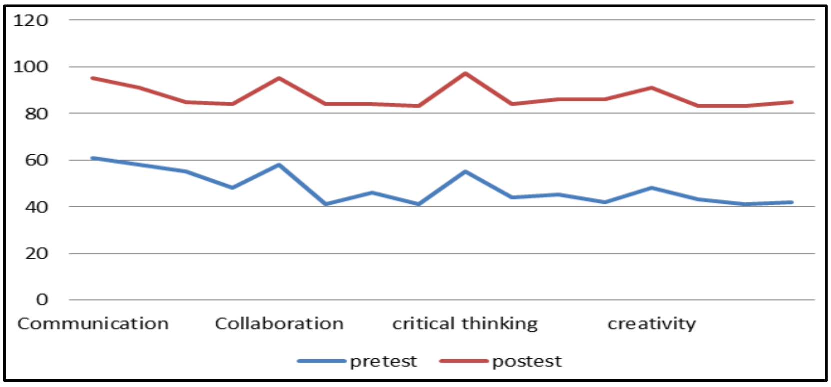

Figure 5. Pretest and Posttest Scores of Students' 4C-Related Skills in the Limited Tryout

Based on Figure 5, the average pretest and posttest scores were 48 and 87.25, respectively. This increase suggests promising improvement trends in students' reported 4C-related skills following use of the developed modules during the pilot implementation. However, these results should be interpreted cautiously because the evaluation employed a one-group pretest–posttest design without a comparison group; therefore, potential influences such as instructor effects, time-on-task, and concurrent learning experiences cannot be ruled out. In addition, because the 4C measures were based on self-reported questionnaires, the observed gains may reflect increased familiarity, perceived improvement, or response tendencies rather than verified competency growth. Accordingly, the findings are presented as preliminary evidence of the module's potential to support 4C-related learning processes rather than conclusive proof of effectiveness.

The observed trends are theoretically plausible because interactive materials can promote active cognitive processing and deeper engagement with learning tasks (Mayer, 2014). Likewise, Canvas features such as discussion boards, peer review, and modular learning can facilitate structured interaction and collaboration, which may align with the intended design of embedding literacy scaffolds across PjBL milestones (Stratton *et al*., 2020). Nevertheless, these references should be understood as explaining possible mechanisms, not as validating causal impact in the current development-study context. Furthermore, the pretest–posttest questionnaire results were analyzed using the normalized gain (N-Gain) to describe the magnitude of change during the limited tryout. The N-Gain results for each 4C indicator are presented in Table 4. The use of N-Gain enables a proportional assessment of improvement by accounting for students' initial performance levels. The findings indicate differential gains across the four competencies, suggesting that certain 4C components were more responsive to the instructional intervention. These results provide preliminary descriptive evidence of learning enhancement while remaining cautious about broader causal interpretation.

Table 4. N-Gain Indicators of Students' 4C-Related Skills in the Limited Tryout

No	4C Skills	Average N-Gain Score	Criteria
1	Communication	0,75	High
2	Collaboration	0,75	High
3	Critical thinking	0,78	High
4	Creativity	0,74	High

Table 4 presents the N-gain scores of students' 4C-related skills following the limited tryout of the Canvas-based interactive General Biology modules integrating scientific literacy scaffolds within PjBL phases. The results indicate high learning gains across all 4C competencies, with critical thinking showing the highest average N-gain (0.78), followed by communication and collaboration (both 0.75), and creativity (0.74). These high scores suggest that the module effectively supports the development of 21st-century skills, providing structured opportunities for students to engage in problem-solving, collaborative tasks, idea generation, and evidence-based reasoning. Overall, the findings provide preliminary evidence that embedding scientific literacy within PjBL activities in a Canvas-supported environment can enhance students' communication, collaboration, critical thinking, and creativity (Thomas, 2000; Trilling & Fadel, 2009). Overall, these N-Gain values indicate high gain categories within this limited setting, supporting the interpretation that the developed modules show potential to support 4C-related outcomes. Future research employing stronger designs (e.g., quasi-experimental comparisons and performance-based assessments) It is recommended to check effectiveness more thoroughly so that obstacles and advantages can be identified and discovered which are sometimes overlooked by quick observation.

Communication Skills

The results show an N-Gain of 0.75 (high category) for students' communication scores after the limited implementation of the developed Canvas-based interactive General Biology modules that embed scientific literacy scaffolds within Project-Based Learning (PjBL) phases**.** However, because these scores were derived from a one group pretestposttest self-report questionnaire**,** the increase should be interpreted cautiously as an indicator of positive perceived improvement or increased communication self efficacy**,** rather than definitive evidence of actual skill enhancement or causal impact. Without a comparison group and without behavioral validation (e.g., analysis of discussion post quality or presentation performance using a validated rubric), the findings cannot rule out response bias, familiarity effects, or other confounding influences.

Within these limitations, the observed trend is pedagogically plausible given the module's design features. The Canvas environment provides structured opportunities for academic interaction through discussion forums, staged project submissions, online presentations, and feedback exchanges, which may encourage students to articulate ideas more frequently in both written and oral forms. Such interactional conditions are consistent with perspectives emphasizing that communication in online learning environments develops through sustained social and cognitive engagement (Garrison *et al*., 2010; Shea

& Bidjerano, 2010). In addition, the scientific literacy scaffolds embedded across project milestones may have helped students frame communication as evidence-based explanation prompting them to interpret data, explain biological phenomena, and justify claims with supporting evidence. This aligns with the view that scientific literacy includes the capacity to communicate scientific knowledge clearly and responsibly in academic and social contexts (OECD, 2019).

The PjBL structure also plausibly contributed to students' perceived communication growth by requiring group discussions, project reporting, and presentations where students must clarify reasoning, defend arguments, and respond to critique. Prior studies have reported that PjBL can support communication development through authentic and collaborative tasks (Guo *et al*., 2020; Kokotsaki *et al*., 2016). Nevertheless, in the present development-study context, these mechanisms should be understood as potential explanations rather than confirmed causes of the N-Gain value. Therefore, the communication findings are best framed as promising preliminary evidence that the validated and practical integrated design may support communication-related learning processes, which is in line with research suggesting that project-based learning supported by LMS platforms can facilitate communication in science learning (Tsybulsky & Muchnik-Rozanov, 2019).

Collaboration Skill

The results show an N-Gain of 0.75 (high category) for students' collaboration scores after the limited implementation of the developed Canvas-based interactive General Biology modules that embed scientific literacy scaffolds within PjBL phases**.** Nevertheless, because the collaboration measure was obtained from a self-report questionnaire in a one-group pretest–posttest setting, the increase should be interpreted cautiously as an indicator of positive perceived improvement, heightened awareness of collaborative processes, or stronger collaboration self-efficacy rather than definitive evidence of actual collaboration skill development. Without complementary evidence from observable behaviors or artifacts (e.g., equity of contribution tracked in Canvas, quality of shared outputs, or structured observation of group dynamics), the current data cannot rule out response bias or satisfaction effects.

Within these methodological boundaries, the reported trend remains pedagogically plausible given the module's design. Canvas provides collaborative affordances such as group workspaces, discussion forums, and group-based assignments that can support role distribution, idea exchange, and shared responsibility for project outputs. Technology-supported collaborative learning has been argued to strengthen social interaction and group performance when learners engage in coordinated tasks and communication (Dillenbourg, 2013; Lai, 2011). In addition, the integration of scientific literacy scaffolds into collaborative activities may have oriented groups toward evidence-based decision making, requiring students to interpret data and justify choices collectively, which is consistent with the view that scientific literacy can be developed through group discussion and may support both conceptual understanding and collaboration (Bybee, 2013).

The PjBL structure further provides a reasonable explanation for why students might perceive stronger collaboration, because projects typically involve complex tasks that demand coordination across planning, implementation, and evaluation stages. Prior studies report that PjBL can foster collaboration and shared responsibility through authentic problem solving and collaborative task completion (Bell, 2010; Han *et al*., 2015). However, in the present development-study context, these references should be treated as a theoretical lens explaining potential mechanisms rather than confirmation that the observed N-Gain reflects causal impact. Therefore, the collaboration results are best framed as promising preliminary indications that the validated and practical integrated module is conducive to collaborative learning conditions, while stronger claims about collaboration skill development would require more objective assessment approaches alongside self-report measures. This cautious interpretation is consistent with studies suggesting that LMS-supported project-based learning can facilitate collaboration in science learning contexts (Lee *et al*., 2014; Zhan *et al*., 2022).

Critical Thinking Skills

The results show that students' critical thinking scores obtained the highest N-Gain value (0.78**,** high category) after the limited implementation of the developed Canvas-based interactive General Biology modules that embed scientific literacy scaffolds within Project-Based Learning (PjBL) phases**.** However, because the gain was derived from a self-reported Likert-scale questionnaire within a one-group pretest–posttest design, the increase should be interpreted cautiously as a preliminary indicator of perceived growth**,** increased awareness of critical thinking processes, or improved confidence in performing such tasks, rather than conclusive evidence that students' analysis, evaluation, and synthesis abilities improved objectively. More direct assessment of critical thinking would require performance-based tasks (e.g., analysis of written arguments, standardized tests, or rubric-scored reasoning artifacts), which were beyond the scope of the present development-oriented implementation.

Within these limitations, the observed improvement trend remains pedagogically plausible given the module's design. The scientific literacy scaffolds embedded across project milestones required students to interpret biological information, evaluate evidence, and justify decisions using reasoning, which aligns with the view that critical thinking develops through engagement with problem contexts that demand analysis and evaluation (Ennis, 2011; Facione, 1990). The PjBL structure further situates students in iterative cycles of inquiry and reflection such as formulating questions, gathering information, and evaluating project outcomes which has been associated with higher-order thinking development in science learning (Guo *et al*., 2020; Hmelo-Silver *et al*., 2007). In addition, Canvas can provide a supportive environment for higher-order engagement through access to resources, structured discussion spaces, and feedback loops that allow students to critique ideas and revise understanding. This is consistent with the notion of cognitive presence as a key element in fostering deeper thinking in online learning environments (Garrison *et al*., 2010; Rolim *et al*., 2019).

Nevertheless, in the present study, these theoretical accounts should be treated as explanatory mechanisms rather than confirmed causal drivers of the observed N-Gain. Therefore, the critical thinking findings are best positioned as promising preliminary indications that the validated and practical integrated modules are conducive to critical thinking–related learning processes, which is broadly consistent with previous reports on LMS-supported project-based learning (Sasson *et al*., 2018). This cautious interpretation also aligns with perspectives emphasizing that scientific literacy integration can support more systematic evaluation and interpretation of scientific phenomena, while realizing that actually having a stronger and more reliable claim requires more direct evidence regarding cognitive performance (Bell, 2010; Bybee, 2013).

Creativity Skills

Students' creativity scores showed an N-Gain of 0.74 (high category) after the limited implementation of the developed Canvas-based interactive General Biology modules that embed scientific literacy scaffolds within Project-Based Learning (PjBL) phases**.** However, because this gain was derived from a self-reported questionnaire within a one-group pretest–posttest design, the result should be interpreted cautiously as a preliminary indicator of perceived creative engagement, creative confidence, or increased willingness to generate ideas, rather than definitive evidence of objectively improved creative competency. Measuring creativity through questionnaires can capture perceptions and attitudes, although it cannot directly evaluate the originality, usefulness or quality of students' creative products.

Within these limitations, the observed improvement trend is pedagogically plausible. PjBL provides learning conditions that can encourage exploration and idea generation by giving students autonomy to design projects, select approaches, and present outputs, which aligns with views that creativity develops when learners are given opportunities to explore within meaningful learning environments (Beghetto & Corazza, 2019; Henriksen et al., 2016). The scientific literacy scaffolds embedded in the module may also have oriented creative work toward scientifically grounded reasoning, requiring students to justify ideas with evidence and align outputs with biological concepts. This is consistent with the argument that creativity in science education should be balanced with conceptual understanding and scientific reasoning (Kind & Kind, 2017).

Canvas may further support creative expression by enabling flexible use of digital formats for project reporting (e.g., videos, posters, infographics, interactive presentations), which can expand students' options for communicating and refining ideas. Digital learning environments have been associated with creativity and innovation development, particularly when they provide tools for creation, sharing, and iteration (Redecker, 2017; Vartiainen et al., 2019). Nevertheless, in the present study these mechanisms should be treated as possible explanations, not confirmed causes of the N-Gain value. Therefore, the creativity findings are best framed as promising preliminary indications that the validated and practical integrated modules are conducive to creative engagement in General Biology learning, which is broadly consistent with reports that digital project-based learning can support creativity (Hsiao *et al*., 2019; Liu *et al*., 2020). To substantiate claims of enhanced creative competency in future research, it would be necessary to analyze actual project artifacts using validated creativity rubrics or performance-based measures, enabling evaluation of originality and quality beyond self-perception.

CONCLUSION

Based on the findings, the Canvas-based interactive General Biology materials integrating scientific literacy scaffolds within Project-Based Learning (PjBL) were successfully developed and met the criteria of validity and practicality. Expert judgment produced an average validity score of 87.55 (valid), indicating that the content and instructional design are aligned with relevant academic and pedagogical standards. Practicality evaluations also showed positive results, with lecturer and student scores of 84.25 and 84.89 (practical), suggesting that the materials are feasible to implement, easy to use, and well accepted in the learning process. In addition to product quality evidence, a limited one-group pretest–posttest tryout yielded promising N-Gain indicators related to students' 4C performance (communication 0.75, collaboration 0.75, critical thinking 0.78, creativity 0.74). These results should be interpreted as preliminary signals of potential benefit rather than definitive proof of effectiveness, given the absence of a comparison group and the single-institution sample. Overall, the study contributes a validated and practical instructional design framework and prototype for integrating PjBL phases, scientific literacy scaffolds, and Canvas features in General Biology, which can serve as a reference for lecturers and as a basis for further studies using stronger experimental or quasi-experimental designs to examine effectiveness more rigorously.

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