

Development and Preliminary Evaluation of Project-Based Learning Teaching Materials for Animal Development Courses to Support Biology Students' Critical Thinking Performance

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Abstract

This study aimed to develop and preliminarily evaluate Project-Based Learning (PjBL)-based teaching materials for the Animal Development course in terms of validity, practicality, learning outcomes, critical-thinking performance, and student attitudes. A research and development approach was employed using the 4D model, consisting of Define, Design, Develop, and Disseminate stages. The developed materials were evaluated by three experts in content, media, and language aspects. Practicality testing involved lecturer responses and a limited trial with six Biology Education students, while field implementation involved 28 students at Universitas PGRI Silampari. Data were collected through expert validation sheets, response questionnaires, achievement tests, critical-thinking performance assessments, and attitude questionnaires. Data analysis was conducted descriptively using percentage scores, mean comparisons, and normalized gain analysis. The results showed that the teaching materials achieved a validity score of 92.71%, indicating a highly valid category. The practicality evaluation obtained an overall score of 87.50%, categorized as highly practical. Students' mean achievement increased from 62.43 in the pretest to 81.25 in the posttest, with a normalized gain score of 0.50. Critical-thinking performance reached an average score of 85.50, while student attitudes toward the learning implementation obtained an average score of 85.50. These findings indicate that the developed PjBL-based teaching materials are feasible and demonstrate promising potential for supporting active, contextual, and reflective learning in biology education. The study implies that integrating project-oriented activities into discipline-specific teaching materials can provide a meaningful framework for fostering students' scientific reasoning and critical-thinking performance.

Keywords: Animal Development; Biology Education; Project-Based Learning; Teaching Materials Development; Critical Thinking Performance.

INTRODUCTION

Contemporary higher education is increasingly expected to prepare students not only to acquire disciplinary knowledge but also to analyze complex information, evaluate evidence, formulate reasoned judgments, solve authentic problems, and communicate scientifically. These competencies represent essential outcomes of twenty-first-century education because graduates are required to navigate complex knowledge environments and apply disciplinary understanding to real-world challenges (OECD, 2019; Schleicher, 2018; van Laar et al., 2020). These competencies are particularly important in science and biology education, where understanding scientific concepts requires students to engage with evidence, interpret relationships among biological phenomena, and construct scientific explanations rather than merely reproduce factual knowledge. Recent studies in science education emphasize that meaningful scientific learning involves participation in scientific practices, including reasoning from evidence, modeling phenomena, argumentation, and explanation construction (Furtak et al., 2018; Osborne, 2019; Kruit et al., 2019). Active and student-centered learning environments have consequently received increasing attention because they provide opportunities for learners to participate directly in inquiry,

collaboration, problem solving, and knowledge construction. Research has demonstrated that learner-centered approaches promote deeper cognitive engagement and support the development of transferable competencies when students are involved in authentic tasks and disciplinary practices (Baeten et al., 2018; Kember & Leung, 2020; Martin et al., 2021). Within this perspective, critical thinking has become a fundamental competence in higher education because university students are expected to evaluate information sources, analyze relationships, construct evidence-based arguments, make justified decisions, and reflect on their reasoning processes (Dwyer et al., 2019; Facione & Facione, 2019; Sutiani et al., 2021).

The need to cultivate these competencies is particularly relevant in undergraduate biology education because many biological phenomena involve complex relationships across molecular, cellular, tissue, and organismal levels (Gomez & Du, 2021; Reinke et al., 2021). Animal Development represents a particularly challenging domain because embryonic development involves dynamic, spatially complex, and temporally coordinated morphological changes that cannot be adequately understood through the memorization of developmental stages alone (Chekrouni et al., 2020; Nurdiani et al., 2019). Understanding embryogenesis requires students to recognize relationships among developmental events, visualize changes in biological structures over time, and connect these transformations with underlying developmental mechanisms. Evidence from embryology education indicates that students may experience difficulties when complex three-dimensional developmental processes are represented primarily through static two-dimensional materials, highlighting the importance of instructional approaches that support visualization, conceptual integration, and reasoning (Chekrouni et al., 2020). In the specific context of Animal Embryology and Reproduction, organizing relationships among concepts through concept mapping has also been associated with analytical thinking and favorable cognitive learning outcomes among Biology Education students (Susetyarini et al., 2023). More importantly, developmental biology education should move beyond the reproduction of factual knowledge toward students' ability to construct

Teaching materials play an important role in facilitating student-centered learning because they can function not merely as repositories of disciplinary information but as instructional scaffolds that structure and guide students' engagement with complex learning tasks. Effective instructional scaffolding can support cognitive and metacognitive processes by organizing learning activities, providing appropriate prompts, directing attention toward relevant information, and assisting students in progressively integrating knowledge and skills (Deep et al., 2020; Doo et al., 2020; Hansen & Richland, 2020). Well-designed teaching materials may therefore integrate learning objectives, conceptual explanations, multiple visual representations, authentic problems, guiding questions, investigation procedures, analytical activities, and reflective prompts into a coherent learning sequence. Such design is particularly important in biology education because students frequently encounter abstract and interconnected processes that require them to coordinate multiple representations and relate observable phenomena to underlying biological mechanisms. Research on complex biological learning has demonstrated the importance of providing structured instructional support to help students connect disciplinary concepts, scientific practices, and representations rather than learning them as isolated components (Deep et al., 2020; Hansen & Richland, 2020; Hidayati et al., 2019). Furthermore, instructional modules incorporating multiple representations and active-learning processes can provide students with opportunities to analyze information and engage in higher-order cognitive activities (Chusni, 2022; Hansen & Richland, 2020; Hidayati et al., 2019). Accordingly, teaching materials in student-centered biology learning should move beyond information transmission toward facilitating active knowledge construction, inquiry, self-regulated learning, scientific reasoning, and communication.

Project-Based Learning (PjBL) provides an appropriate pedagogical framework for designing teaching materials with these characteristics because it organizes learning around meaningful questions, authentic tasks, collaborative inquiry, investigation, product development, communication, and reflection. Empirical evidence indicates that PjBL can promote student engagement through collaborative, disciplinary, iterative, and authentic learning experiences, particularly when project activities are systematically aligned with learning objectives and

instructional support (Almulla, 2020; Fajar et al., 2020; Hizqiyah et al., 2023). Within biology education, PjBL has been used to engage students in interpreting biological phenomena, communicating scientific ideas, developing higher-order thinking, and connecting conceptual knowledge with scientific practices (Fajar et al., 2020; Permana & Chamisijatin, 2019; Hizqiyah et al., 2023). More recent evidence from undergraduate biology education further indicates that project-based activities can support conceptual understanding and science-process performance when students are actively involved in investigation and application of disciplinary knowledge (Abas et al., 2024). Collectively, these findings strengthen the rationale for integrating PjBL directly into Animal Development teaching materials, where students are required not only to understand developmental concepts but also to investigate biological phenomena, analyze evidence, communicate scientific explanations, and reflect on their learning processes.

Critical thinking represents one of the higher-order competencies that may particularly benefit from appropriately structured project-based environments. However, critical thinking does not necessarily emerge merely because students participate in projects; rather, its development depends on how project tasks are designed to promote questioning, investigation, evidence analysis, reasoning, decision making, and reflection (Maor et al., 2023; Sasson et al., 2018; Shi & Li, 2024). Project-based environments that incorporate explicit scaffolding, teacher guidance, peer interaction, metacognitive regulation, and reflective practices provide stronger conditions for students to engage in higher-order cognitive processes (Wu, 2024; Zhong & Lyu, 2022). Moreover, evidence from higher education suggests that authentic, disciplinary, collaborative, and iterative project experiences can strengthen students' engagement with complex problems and support advanced thinking processes (Almulla, 2020; Barak & Yuan, 2021; Chang et al., 2024). These findings indicate that the pedagogical value of PjBL lies not simply in assigning a project but in deliberately structuring the cognitive, metacognitive, collaborative, and reflective processes embedded within the project experience.

Despite the potential of PjBL to support higher-order learning, recent evidence indicates that its outcomes are highly dependent on instructional design and contextual conditions. The effectiveness of project-based environments can vary according to teacher guidance, student participation, disciplinary context, institutional setting, scaffolding, authenticity of the project, and opportunities for metacognitive regulation (Barak & Yuan, 2021; Chang et al., 2024; Shi & Li, 2024; Wu, 2024; Zhong & Lyu, 2022). Moreover, discipline-specific studies in biology have tended to examine PjBL as an instructional intervention applied to particular topics, such as histology and ecosystems, rather than systematically embedding project processes, critical-thinking indicators, learning resources, assessment criteria, and reflective tasks within an integrated teaching-material package (Khafah et al., 2023; Permana & Chamisijatin, 2019). This condition provides a relevant research space for developing discipline-specific instructional products in which PjBL is operationalized directly within the organization of biological content, learning activities, assessment, and critical-thinking processes.

This research need is particularly relevant to Animal Development instruction. In the Biology Education Study Program at Universitas PGRI Silampari, the course had predominantly been delivered through theoretical lectures and discussions, whereas the characteristics of Animal Development content provide substantial opportunities for observation, investigation, interpretation, project development, scientific communication, and reflection. The present study therefore differs from studies that primarily apply PjBL as an instructional strategy by developing a structured teaching-material package in which Animal Development concepts are systematically integrated with problem identification, project-question formulation, project planning and task distribution, utilization of learning resources, observation and data collection, data processing and analysis, product development, collaboration, communication, and reflection. This integration is particularly significant because it positions critical thinking not as an isolated learning outcome but as a disciplinary practice embedded throughout project implementation. The novelty of the study consequently lies in the systematic integration of Animal Development content, PjBL syntax, project-process assessment, critical-thinking indicators, and reflective learning activities within a

unified set of teaching materials. Accordingly, this study aimed to develop and preliminarily evaluate PjBL-based Animal Development teaching materials for Biology Education students in terms of expert-validated quality, practicality, student learning outcomes, critical-thinking performance, and student attitudes toward learning.

METHODS

Research Design and Development Procedure

This study employed a research and development (R&D) design to develop and preliminarily evaluate Project-Based Learning (PjBL)-based teaching materials for the Animal Development course in Biology Education. The R&D approach was selected because the primary purpose of the study was to systematically design, validate, revise, and evaluate an instructional product rather than merely examine the effect of an instructional intervention. Educational design and development research emphasizes the systematic construction and refinement of instructional products through theory-informed design, prototyping, evaluation, and iterative revision (Burkhardt & Schoenfeld, 2021; Reinmann, 2020).

The development procedure followed the 4D model proposed by Thiagarajan et al. (1974), consisting of four stages: Define, Design, Develop, and Disseminate. The Define stage involved analyzing learning requirements, student characteristics, learning tasks, essential concepts, and learning objectives related to Animal Development. The Design stage focused on developing the initial structure of the teaching materials by integrating PjBL components. The Develop stage consisted of expert validation, product revision, practicality testing, and field implementation, while the Disseminate stage involved distributing the validated teaching materials to students. The use of the 4D model for systematic teaching-material development, expert validation, revision, and limited-scale testing has also been demonstrated in recent educational development research (Ihsan et al., 2023; Amalia et al., 2024).

The integration of PjBL into the teaching materials was designed to provide students with opportunities to engage in authentic biological problems, investigate developmental phenomena, analyze information, construct explanations, communicate findings, and reflect on their learning processes. Such characteristics are consistent with research describing project-based learning in science education as a student-centered and problem-oriented approach that supports the integration, application, and construction of knowledge through project activities (Markula & Aksela, 2022; Shin et al., 2021). In the context of Biology Education, recent evidence from an Invertebrate Zoology course also indicates that integrating PjBL can support students' scientific process skills and conceptual understanding (Abas et al., 2024).

Participants and Research Setting

The study was conducted in the Biology Education Study Program at Universitas PGRI Silampari. The participants consisted of Biology Education students enrolled in the Animal Development course. The expert validation stage involved three experts representing different evaluation domains: a subject-matter expert, a media expert, and a language expert. Following expert evaluation and revision, a limited practicality trial was conducted involving six Biology Education students. Subsequently, a field implementation was conducted with 28 Biology Education students to obtain preliminary evidence regarding learning outcomes, critical-thinking performance, and student attitudes toward the developed teaching materials.

The selection of participants was based on their involvement in the Animal Development course, where the developed teaching materials were implemented. Because this study focused on educational product development and preliminary evaluation, the field implementation was designed to examine product feasibility and instructional potential within the intended learning context rather than to establish causal effectiveness.

Development Product and Instructional Characteristics

The developed product consisted of PjBL-based teaching materials specifically designed for the Animal Development course. Unlike conventional instructional materials that primarily present

biological concepts, the developed materials incorporated learning activities that guided students through scientific practices. The materials included conceptual explanations, project instructions, guiding questions, learning resources, investigation activities, data analysis tasks, product development activities, presentation activities, and reflection components.

The instructional structure was designed to connect biological concepts with authentic developmental phenomena. Students were guided to identify biological problems, formulate project questions, collect and analyze information, collaborate with peers, communicate findings, and evaluate their learning processes. This design was intended to support the integration of conceptual understanding and critical-thinking practices within undergraduate biology learning.

Instruments and Data Collection

Data were collected using several instruments, including expert validation sheets, practicality questionnaires, learning achievement tests, critical-thinking performance assessment sheets, and student attitude questionnaires.

The expert validation instruments were used to evaluate the quality of the developed teaching materials from three perspectives. The subject-matter expert assessed content accuracy, relevance, depth, organization, and suitability of learning activities. The media expert evaluated visual presentation, layout, readability, and technical aspects of the teaching materials. The language expert assessed sentence structure, clarity, terminology, communicativeness, and language accuracy. The validation process also included qualitative comments from experts that were used as the basis for product revision.

The practicality instruments were administered to lecturers and students after the teaching materials were introduced. The lecturer questionnaire evaluated the usability and feasibility of the materials during learning implementation, whereas the student questionnaire examined students' perceptions regarding readability, attractiveness, clarity of instructions, and ease of use. The limited student trial involved six students before the field implementation stage.

Learning outcomes were measured using achievement tests administered before and after the implementation of the teaching materials. Critical-thinking performance was assessed during project activities through eight indicators: identification of problems and project questions, project planning and task distribution, use of teaching materials and learning resources, observation and data collection, data processing and analysis, collaboration and responsibility, communication of project results, and reflection on project evaluation. Student attitudes were measured using a questionnaire evaluating students' responses toward the implementation of PjBL-based Animal Development learning.

Data Analysis

The collected data were analyzed descriptively to determine the quality and instructional potential of the developed teaching materials. Expert validation and practicality data were analyzed by calculating percentage scores based on obtained scores compared with maximum possible scores. The resulting percentages were interpreted using predetermined category criteria to determine the level of validity and practicality.

Student learning outcomes were analyzed by comparing mean pretest and posttest scores. The improvement in achievement was calculated using normalized gain (N-gain) analysis. Critical-thinking performance and student attitude data were analyzed using mean scores and category interpretations. Because the research design involved a single-group implementation without a comparison group, the findings were interpreted as preliminary descriptive evidence regarding the feasibility and instructional potential of the developed materials rather than definitive evidence of causal effectiveness. This analytical approach is consistent with educational product-development research, where formative evaluation emphasizes determining product quality, usability, and potential contribution before conducting stronger experimental evaluations.

RESULT AND DISCUSSION

Development and Expert Validation of PjBL-Based Animal Development Teaching Materials

The development process produced Project-Based Learning (PjBL)-based teaching materials for the Animal Development course. The developed materials integrated biological concepts with project-oriented learning activities, including problem identification, project planning, information exploration, observation, data analysis, product development, presentation, and reflection. The instructional structure was designed to support students in connecting theoretical understanding of animal developmental processes with authentic biological phenomena and scientific inquiry activities.

The developed teaching materials were evaluated by three experts consisting of a subject-matter expert, a media expert, and a language expert. The validation process assessed the suitability of the content, presentation quality, visual design, readability, and language accuracy. The experts also provided qualitative recommendations related to strengthening contextual biological examples, improving visual representations of developmental processes, and refining language clarity. These suggestions were incorporated into the final revision of the teaching materials.

As presented in Table 1, the developed teaching materials obtained a total validation score of 89 out of 96 points, equivalent to 92.71%, and were categorized as highly valid. The highest percentage was obtained in the language aspect (94.44%), followed by media validation (93.75%) and material validation (89.29%). These findings indicated that the developed materials fulfilled the required criteria regarding content accuracy, technical presentation, and linguistic quality.

Table 1. Expert Validation Results of PjBL-Based Animal Development Teaching Materials

Validation Aspect	Maximum Score	Obtained Score	Percentage (%)	Category
Material Content Validation	28	25	89.29	Highly Valid
Media Design Validation	32	30	93.75	Highly Valid
Language Validation	36	34	94.44	Highly Valid
Total	96	89	92.71	Highly Valid

Practicality Evaluation of the Developed Teaching Materials

The practicality evaluation was conducted through lecturer responses and a limited student trial. The lecturer evaluation examined the suitability of the teaching materials for classroom implementation, while the student trial evaluated students' perceptions regarding readability, attractiveness, clarity of instructions, and ease of use.

As shown in Table 2, the lecturer response obtained a score of 85.00%, while the small-group student trial achieved 90.00%. The overall practicality score was 87.50%, which was categorized as highly practical. These findings indicated that the developed teaching materials were considered feasible and understandable for supporting project-based learning activities in the Animal Development course.

Table 2. Practicality Evaluation of PjBL-Based Animal Development Teaching Materials

Evaluation Source	Participants	Obtained Score	Maximum Score	Percentage (%)	Category
Lecturer Response	1 Lecturer	34	40	85.00	Highly Practical
Student Small-Group Trial	6 Students	271	300	90.00	Highly Practical
Overall Practicality	-	-	-	87.50	Highly Practical

Students' Learning Outcomes After Implementation of the Teaching Materials

The field implementation was conducted with 28 Biology Education students enrolled in the Animal Development course. Students completed achievement tests before and after participating in learning activities using the developed PjBL-based teaching materials.

As presented in Table 3, students' mean achievement score increased from 62.43 on the pretest to 81.25 on the posttest. The difference between the two measurements was 18.82 points. Furthermore, the normalized gain value was 0.50, indicating a moderate improvement category.

Table 3. Comparison of Students' Learning Outcomes Before and After Implementation

Assessment	Number of Students (N)	Minimum Score	Maximum Score	Mean Score
Pretest	28	45.00	80.00	62.43
Posttest	28	66.35	96.00	81.25
Mean Difference	-	-	-	18.82
Improvement Indicator			Value	
Normalized Gain (N-gain)			0.50	
Interpretation			Moderate	

To provide a clearer visualization of students' learning outcome changes, the comparison between pretest and posttest mean scores is presented in Figure 1. Learning Achievement Score

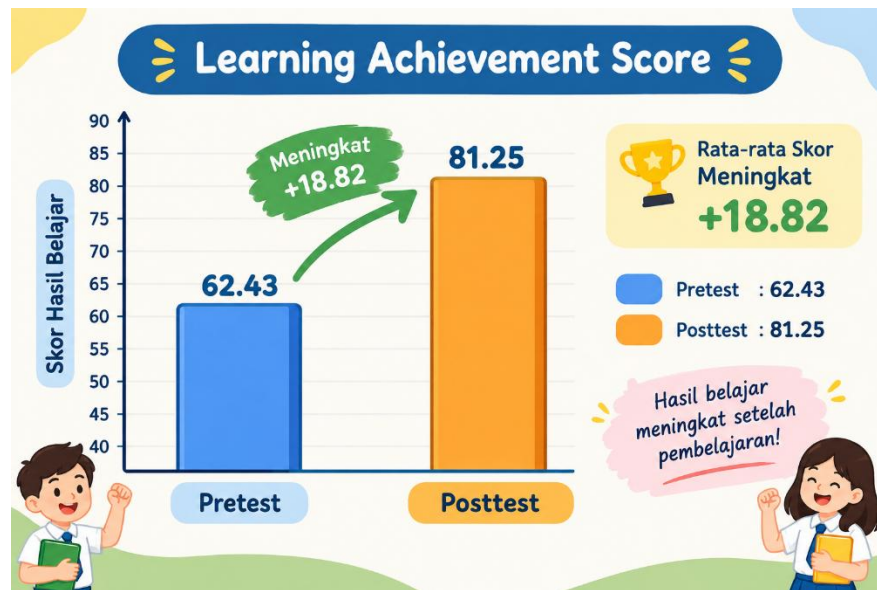
**Figure 1.** Comparison of Students' Mean Scores Before and After Implementation of PjBL-Based Teaching Materials

Figure 1 illustrates that the average student achievement score increased after the implementation of the developed teaching materials. The posttest mean score was higher than the pretest mean score, indicating a positive change in students' achievement during the implementation period.

Students' Critical-Thinking Performance During Project Activities

Students' critical-thinking performance was assessed during project implementation based on eight indicators: identification of problems and project questions, project planning and task distribution, use of teaching materials and learning resources, observation and data collection, data processing and analysis, collaboration and responsibility, communication of project results, and reflection on project evaluation.

As shown in Table 4, students achieved an overall critical-thinking performance score of 85.50, categorized as very good. The highest scores were obtained in problem identification (9.50/10), project planning and task distribution (13.50/15), and utilization of teaching materials and learning resources (13.50/15). Meanwhile, communication of project results (8.00/10) and reflection on project evaluation (7.00/10) obtained comparatively lower scores.

Table 4. Students' Critical-Thinking Performance During Project Implementation

Critical-Thinking Indicator	Maximum Score	Mean Score	Category
Identification of Problems and Project Questions	10	9.50	Very Good
Project Planning and Task Distribution	15	13.50	Very Good
Use of Teaching Materials and Learning Resources	15	13.50	Very Good
Observation and Data Collection	15	12.75	Very Good
Data Processing and Analysis	15	12.75	Very Good
Collaboration and Responsibility	10	8.50	Very Good

Communication of Project Results	10	8.00	Good
Reflection on Project Evaluation	10	7.00	Good
Overall Performance	100	85.50	Very Good

Students' Attitudes Toward PjBL-Based Animal Development Learning

Students' attitudes toward the implementation of the developed teaching materials were evaluated using a questionnaire consisting of 20 statements. The questionnaire examined students' responses toward learning engagement, learning experience, and acceptance of the developed materials.

As presented in Table 5, students obtained scores ranging from 77 to 96, with an average score of 85.50 out of 100. The result indicated that students demonstrated positive attitudes toward the implementation of PjBL-based Animal Development teaching materials.

Table 5. Students' Attitudes Toward PjBL-Based Animal Development Learning

Assessment Component	Number of Items	Score Range	Mean Score	Category
Student Attitude Questionnaire	20	77–96	85.50	Very Positive

Overall, the developed PjBL-based Animal Development teaching materials achieved high validity (92.71%) and practicality (87.50%). The field implementation showed a descriptive increase in students' learning achievement, with the mean score increasing from 62.43 to 81.25 and a normalized gain score of 0.50. Students also demonstrated strong critical-thinking performance (85.50) and positive attitudes toward the learning implementation (85.50). These findings indicated that the developed teaching materials were feasible and showed promising instructional potential for supporting active and reflective biology learning.

Discussion

The high validity of the developed teaching materials indicates that the product achieved substantial alignment among disciplinary content, instructional organization, visual presentation, and linguistic clarity. More importantly, validity in the present study should not be interpreted merely as a numerical judgment provided by experts, but as evidence that the instructional components were sufficiently coherent to operationalize Animal Development concepts through structured project activities. Educational design research emphasizes that the quality of an instructional product depends on the systematic alignment of its intended objectives, content, learning activities, assessment procedures, and intended users, followed by formative evaluation and iterative refinement before broader implementation (McKenney & Reeves, 2019; Nieveen & Folmer, 2013). Accordingly, the expert-validation process served two complementary functions in this study: establishing the appropriateness of the product and identifying specific aspects requiring refinement before field implementation.

This alignment is particularly important in Animal Development because students must understand interconnected and temporally sequenced biological processes rather than isolated factual information. Consequently, instructional materials for this domain need to facilitate connections among biological structures, developmental mechanisms, observable phenomena, and evidence-based explanations. The integration of disciplinary content with project activities in the developed materials therefore represents more than a modification of presentation format; it transforms the teaching materials into an instructional scaffold through which students can identify biological problems, organize investigations, collect and interpret information, construct products, communicate findings, and reflect on their learning processes. This interpretation is consistent with evidence showing that PjBL is most productive when learning activities are systematically structured around meaningful tasks rather than when projects are treated merely as supplementary assignments (Almulla, 2020; Barak & Yuan, 2021; Sasson et al., 2018). Sasson et al. (2018), for example, demonstrated that a structured PjBL environment can support critical thinking and question-posing when students are provided with opportunities to engage actively with problems and knowledge construction. Similarly, Barak and Yuan (2021) showed that contextualized and well-structured project experiences can facilitate advanced forms of thinking. These studies

reinforce the importance of instructional structure in explaining why the materials developed in the present study achieved strong expert-validation outcomes.

The practicality findings provide a complementary perspective on product quality because they indicate whether an instructional design that appears theoretically appropriate can also be implemented by its intended users. The positive responses from lecturers and students suggest that the developed materials provided a sufficiently clear and manageable learning pathway for project implementation. Rather than attributing this practicality simply to the attractiveness or readability of the product, it can be interpreted in relation to the explicit organization of project stages, including problem identification, project planning, investigation, data analysis, product development, presentation, and reflection. Such sequencing is important because PjBL involves multiple interdependent activities that can generate substantial cognitive and organizational demands when students receive insufficient guidance. Almulla (2020) similarly emphasized the importance of collaborative, disciplinary, iterative, and authentic learning processes in creating productive PjBL environments. More specifically, Zhong and Lyu (2022) demonstrated that students' engagement in project-based environments is supported by scaffolding through teacher direction, technological support, and peer collaboration. Thus, the practicality observed in the present study may reflect not merely the usability of the teaching materials as a physical or textual product, but their capacity to scaffold students through increasingly complex project activities.

This interpretation is also consistent with recent evidence suggesting that the outcomes of project-based approaches are highly dependent on implementation conditions. PjBL cannot be assumed to produce meaningful learning simply because students complete a project; its instructional value depends on the extent to which project activities are aligned with disciplinary objectives, supported by appropriate scaffolding, and accompanied by opportunities for collaboration, monitoring, feedback, and reflection. Shi and Li (2024) showed that the implementation of PjBL in higher education is influenced by interacting factors related to instructional design, teacher guidance, student participation, disciplinary context, and institutional conditions. Likewise, research on self-regulated learning in project-based environments has highlighted the importance of metacognitive support and reflective practices in helping students manage complex project tasks (Wu, 2024). Consequently, the positive practicality findings of the present study are theoretically meaningful because the developed materials did not simply instruct students to produce a project; they organized the project process into explicit and interconnected learning phases.

The discipline-specific nature of the developed product further distinguishes the present study from research that treats PjBL primarily as a general classroom intervention. Evidence from biology education demonstrates that project-based approaches can be productive when they are deliberately adapted to the epistemic and conceptual characteristics of biological content. For example, Tuaputty et al. (2023) reported that laboratory-oriented PjBL in marine biology supported learning outcomes and critical thinking by involving students directly in investigating and verifying biological phenomena. Such findings are particularly relevant to the present study because Animal Development similarly requires students to move between conceptual knowledge and the interpretation of biological processes. The current product extends this orientation by embedding project stages directly within teaching materials rather than treating PjBL as a separate instructional procedure imposed on conventional course materials.

Taken together, the validity and practicality findings provide complementary evidence concerning the quality of the developed product. Expert validation established the conceptual, instructional, visual, and linguistic appropriateness of the materials, whereas lecturer and student responses provided evidence regarding their usability within the intended learning context. The contribution of the study therefore lies not simply in producing another set of course materials, but in demonstrating a discipline-specific instructional design in which Animal Development content, PjBL processes, critical-thinking activities, assessment indicators, and reflection are organized within a unified learning resource. Nevertheless, these findings should be interpreted as evidence of product feasibility rather than definitive evidence of instructional effectiveness. Establishing

whether this integrated design produces superior learning and critical-thinking outcomes requires subsequent comparative studies involving control conditions, larger samples, and direct pretest–posttest measures of critical thinking.

CONCLUSION

This study developed and preliminarily evaluated Project-Based Learning (PjBL)-based teaching materials for the Animal Development course in Biology Education. The developed materials demonstrated high validity based on expert evaluation and high practicality based on lecturer and student responses, indicating that the product was appropriate and feasible for supporting project-oriented biology learning. The implementation of the teaching materials was accompanied by positive changes in students' learning achievement, with an increase in mean scores from pretest to posttest and a moderate normalized gain value. Students also demonstrated strong critical-thinking performance during project activities and showed positive attitudes toward the learning process. The main contribution of this study lies in the development of a discipline-specific instructional product that integrates Animal Development concepts, PjBL stages, critical-thinking indicators, and reflective learning activities into a coherent learning framework. These findings suggest that systematically designed project-based teaching materials can provide meaningful support for active, contextual, and inquiry-oriented biology education. However, the findings should be interpreted as preliminary evidence because the study was conducted using a limited sample and a single-group implementation design. Future research should investigate the effectiveness and transferability of the developed materials through larger-scale implementations, comparative research designs, and more comprehensive measurements of students' critical-thinking development.

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