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Enhancing Critical Thinking Skills of Biology Students Through the Development of STEM-Based Invertebrate Zoology Teaching Materials

Kasmiruddin[1*], Endang Widi Winarni[2], Abdul Rahman[2]

[1]Faculty of Teacher Training and Education, Universitas Muhammadiyah Bengkulu, Bengkulu, Indonesia.
[2]Faculty of Teacher Training and Education, Universitas Bengkulu, Bengkulu, Indonesia.

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Corresponding Author:
Kasmiruddin
kasmiruddin@umb.ac.id

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Abstract: This study aimed to enhance biology students' critical thinking skills through the development of STEM-based instructional materials for the Invertebrate Zoology course. Employing a design and development research approach using the ADDIE model, the study involved needs analysis, module development, expert validation, practicality testing, and effectiveness evaluation. The materials integrated STEM elements including ecological measurement tools, technological media, specimen preparation, and data analysis. Validation by experts yielded a 98% score, indicating high validity. Practicality tests showed increasing student satisfaction across individual (83.47%), small group (85.66%), and full-class trials (94.30%). The effectiveness was assessed using a one-group pretest-posttest design. The Wilcoxon Signed-Rank test revealed a statistically significant improvement in students' critical thinking skills (p = 0.000). Posttest results showed that 66.67% of students reached the "very good" category and 33.33% were in the "good" category, with a mean score of 84%. Among Ennis' critical thinking indicators, "defining terms" had the highest score (95.24%), while "generalizing from evidence" scored the lowest (72.38%). These findings indicate that STEM-integrated teaching materials can effectively foster students' higher-order thinking in biology education.

Keywords: Biology teaching; Critical thinking; Instructional materials; Invertebrate zoology; STEM education

Introduction

In the evolving landscape of 21st-century education, equipping students with higher-order thinking skills such as critical thinking has increasingly been recognized as a central educational goal (Ngatminiati et al., 2024; OECD, 2018; Trilling & Fadel, 2009). Critical thinking, defined as the ability to analyze, evaluate, and synthesize information logically and reflectively, is particularly vital in the sciences, where evidence-based reasoning and decision-making are crucial (Azrai et al., 2020; Dwyer et al., 2014; Halpern & Dunn, 2021). Previous research has also shown that integrating STEM with project-based learning effectively enhances students' critical thinking skills, even at the elementary school level (Lestari et al., 2024).

Within the field of biology, which spans topics ranging from molecular mechanisms to ecosystem dynamics, students are expected not only to master core content knowledge but also to develop the cognitive skills required to understand complex systems and solve real-world problems. These skills are essential for academic achievement as well as for preparing future scientists and educators to address pressing societal and environmental challenges (Ratih et al., 2024).

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Despite this growing emphasis, preliminary classroom observations at the Biology Education Program of Universitas Muhammadiyah Bengkulu (UM Bengkulu) reveal significant challenges in students' critical thinking development. Data collected from one of the biology courses indicate that only 48% of students were able to answer HOTS-based questions at the C4 level, 33% at the C5 level, and just 22.9% at the C6 level. These low percentages suggest that students struggle with higher-order reasoning tasks, leading many instructors to hesitate in incorporating advanced cognitive assessments into their teaching. In addition, 85% of students reported a lack of relevant teaching materials for invertebrate zoology, while 100% expressed a need for more engaging instructional resources. These findings highlight a gap not only in cognitive engagement but also in instructional support, particularly for a course as content-rich and observational as invertebrate zoology. These results are consistent with Cahaya et al. (2024), who found that misconceptions among biology education students were largely due to limited exposure to higher-order thinking skills (HOTS)-based assessments. Their study revealed that students often struggled to analyze and connect information to existing biological concepts, resulting in persistent misconceptions that hinder the development of critical thinking. Critical thinking is indeed essential in 21st-century education, yet Indonesian students continue to perform at relatively low levels in this domain, as reflected in PISA results and corroborated by local studies (Heryani et al., 2023).

Traditional approaches to biology education often rely heavily on didactic instruction and rote memorization, which restrict opportunities for students to engage in scientific reasoning and practice critical thinking (Santi et al., 2018; Yaki, 2022). This limitation is particularly evident in sub-disciplines such as invertebrate zoology, where instruction typically focuses on taxonomy and morphology through lectures or textbook readings. Despite the richness and ecological importance of invertebrates, the potential of this subject to foster analytical and reflective thinking is often underutilized. Therefore, innovative teaching strategies are required to make the subject more inquiry-based, contextual, and cognitively stimulating (Abas et al., 2024; Yaki, 2022).

One promising solution lies in the integration of STEM (Science, Technology, Engineering, and Mathematics) principles into biology education. STEM-based teaching emphasizes hands-on learning, technological engagement, problem-solving, and data interpretation, providing students with authentic learning experiences that mirror scientific practice (Novitasari et al., 2024). Research has shown that STEM education enhances critical thinking, promotes conceptual understanding, fosters reflective and creative thinking, and develops essential 21st-century skills such as collaboration, communication, innovation, and digital literacy (Kusmiarti, 2023; Pahrudin et al., 2021; Hasancebi et al., 2021; Lestari et al., 2018; Benek & Akcay, 2022). Moreover, STEM-based instruction encourages students to act as investigators, constructing knowledge through evidence and justifying their reasoning with scientific arguments (Pratama & Cahaya, 2025). The integration of STEM with problem-based learning has been shown to strengthen not only conceptual understanding but also students' reasoning and analytical abilities (Gusman et al., 2023). Experiential learning within a STEM framework enables learners to connect real-world phenomena with abstract concepts, thereby fostering higher-order thinking skills such as analysis, inference, and evaluation (Khairati et al., 2021).

Nevertheless, STEM integration in undergraduate biology—particularly in invertebrate zoology—remains limited and often fragmented. Courses are still commonly presented as standalone theoretical units, overlooking the rich opportunities for field-based exploration, ecological data collection, and interdisciplinary learning (Abas et al., 2024; Yaki, 2022). Recognizing these gaps, this study aims to design and evaluate STEM-based teaching materials for invertebrate zoology that integrate scientific inquiry, fieldwork tools, specimen analysis, and mathematical data interpretation. This instructional model seeks to shift learning from passive memorization to active exploration and from abstract content to authentic problem-solving.

Critical thinking skills are among the most essential competencies in 21st-century science education, yet Indonesian students still show relatively low achievement in this domain. To address this challenge, innovative approaches such as STEM-based learning integrated with design thinking have been increasingly emphasized. A recent meta-analysis by Zulyusri et al. (2023) revealed that STEM learning combined with design thinking had a substantial effect (ES = 0.84) on enhancing students' critical thinking skills. This finding underscores the importance of embedding authentic problem-solving and creative design processes into science instruction to foster higher-order thinking.

Ultimately, this research contributes to the ongoing effort to reimagine science education by embedding STEM principles into course design, thereby equipping biology students to become thoughtful, critical, and reflective learners prepared to thrive in a complex, data-driven world.

Method

This study employed a research and development (R&D) approach with the primary goal of producing STEM-based teaching materials for the Invertebrate Zoology course. The objective was to enhance the critical thinking skills of undergraduate biology students at the Faculty of Teacher Training and Education (FKIP), Universitas Muhammadiyah Bengkulu.

The ADDIE development model was selected as the framework because of its systematic and iterative nature, consisting of five phases: Analysis, Design, Development, Implementation, and Evaluation. This model enables continuous refinement throughout the development process, thereby ensuring the validity, practicality, and effectiveness of the resulting instructional materials (Branch, 2009).

The use of the ADDIE model in this study is supported by its successful application in previous instructional design research. For example, Pratama et al. (2024) implemented the model in the development of a bacteriology textbook, which was validated by experts and proven to be both practical and effective in supporting student learning.

Analysis Phase

This stage began with a comprehensive needs analysis using questionnaires and interviews with students and lecturers. The analysis examined three aspects: deficiencies in the current materials, essential learning needs, and user expectations. The data revealed that students perceived existing materials as lacking clarity, relevance, and technological support. These findings reflected an urgent demand for instructional resources that are more contextual, interactive, and integrated with digital and field-based learning.

Design Phase

The teaching module was carefully designed to incorporate STEM components throughout both theoretical and practical activities. It included an introduction to the course, clearly defined learning outcomes and indicators, inquiry-driven activities integrating STEM elements, embedded QR codes linking to online references and resources, evaluation instruments, and relevant literature. The activities were developed to foster scientific exploration through observation, ecological measurement, and problem-solving, all of which mirror authentic scientific practices.

Development Phase

This phase involved aligning sub-learning outcomes with the Semester Learning Plan (RPS) and identifying the shortcomings of the previous instructional materials. The content was enhanced by integrating aspects of science, technology, engineering, and mathematics into each core topic. Instruments were developed for expert validation, student practicality assessments, and critical thinking evaluation. Subject matter experts and practitioner reviewers provided feedback, leading to iterative improvements in clarity, design, and STEM alignment. Trials were conducted in three stages: individual, small group, and full-class testing to ensure the product's usability and effectiveness.

Implementation Phase

After validation, the module was implemented in a real classroom setting. The researcher served as the instructor, supported by an observer from the teaching staff. Participants consisted of 21 third-semester students enrolled in the Invertebrate Zoology course. The research employed a one-group pretest-posttest design, with critical thinking performance evaluated before and after the intervention using an assessment rubric based on Ennis' indicators.

Evaluation Phase

Evaluation occurred both formatively and summatively. Formative evaluation guided revisions during each development stage, while summative evaluation assessed the final product's effectiveness in enhancing students' critical thinking skills and its alignment with learning objectives.

Participants

The participants were drawn from the third-semester cohort of the Biology Education Program at FKIP UM Bengkulu. A total of 21 students took part in the full-class implementation trial.

Data Collection Techniques and Instruments

This study used a combination of tests, interviews, and questionnaires. The pretest and posttest assessed students' critical thinking performance before and after the use of the teaching materials. Interviews conducted during the needs analysis phase captured student and lecturer insights on instructional challenges and expectations. Questionnaires were used throughout the process to evaluate needs, validate content and structure, and gauge student satisfaction and practicality of the materials.

To support this data collection, several instruments were developed. These included a student needs assessment form, expert validation rubrics for both the RPS and critical thinking test items, and a checklist for evaluating the teaching module. Ennis-based critical thinking tests and rubrics were used to assess the outcomes, and student response questionnaires evaluated practicality and user experience. All instruments used Likert-scale scoring and were subjected to validity and reliability testing before full deployment.

Data Analysis

The results of the student needs assessment were converted into percentages and categorized using qualitative descriptors such as "very good" or "sufficient" to prioritize features in instructional design. Expert validation data were analyzed by calculating average percentage scores, with ≥ 81.25% considered highly valid. Practicality responses were also quantified using percentage scoring, with values ≥ 61% indicating the material was suitable for classroom use. For the effectiveness evaluation, pretest and posttest scores were compared using the Wilcoxon Signed-Rank Test, as the design involved one group. A p-value below 0.05 was interpreted as a statistically significant improvement in critical thinking performance.

Result and Discussion

Student Needs and the Rationale for STEM-Based Teaching Material Development

The analysis of student needs in the Invertebrate Zoology course reveals a substantial gap between existing teaching materials and student expectations. Survey results show that 85% of students preferred field-based learning, while 84% desired greater use of laboratory tools and digital technology. Additionally, 75% reported that the current materials were difficult to understand, and 68% indicated low engagement levels and insufficient stimulation of critical thinking.

These findings suggest that traditional materials often fail to connect with students' real-world experiences and preferred learning styles. The lack of contextual relevance and interactivity not only limits conceptual understanding but also reduces students' motivation to engage with complex biological content. Effective STEM integration has the potential to bridge this gap by contextualizing science learning, fostering curiosity, and encouraging higher-order thinking (Zulkarnain & Tanjung, 2023; Heryani et al., 2023; Sari et al., 2021).

In light of these results, the rationale for developing STEM-based teaching materials becomes clear. Integrating Science, Technology, Engineering, and Mathematics not only enhances content delivery but also equips students with critical thinking, problem-solving, and analytical skills. These competencies are particularly essential in understanding biodiversity within invertebrate zoology, a subject that requires both theoretical knowledge and hands-on application. Consequently, the STEM framework aligns well with the pedagogical need for instructional materials that are cognitively challenging, ecologically relevant, and technologically adaptive (Karunia & Ridlo, 2022; Laksono et al., 2021; Pratiwi & Rachmadiarti, 2021).

Design and Features of the STEM-Based Teaching Material

The development of STEM-based teaching materials was grounded in both ecological relevance and pedagogical considerations. Three phyla—Mollusca, Arthropoda, and Echinodermata—were deliberately selected because of their diversity, availability in local ecosystems, and observable anatomical features, all of which facilitate meaningful field-based learning experiences (Weldi, 2020). These selections ensure both curricular alignment and practical feasibility for undergraduate-level biology education.

The design incorporates modules that combine theoretical background, STEM-based activities, HOTS-aligned student worksheets (LKS), and QR codes linking to external learning resources. These features directly respond to the student needs identified in the survey. For instance, students' preference for technology integration is addressed through digital features such as interactive simulations, videos, and field guides. These technological components serve dual purposes: strengthening conceptual understanding and fostering digital literacy (Tene et al., 2024). Furthermore, the development of effective instructional materials requires complementary assessment tools that can accurately measure students' higher-order thinking skills (Sari et al., 2023).

Engineering elements, such as sample preservation and slide preparation, train students in procedural and technical skills, while mathematical activities—such as density calculations and statistical analysis—promote data-driven reasoning. Within the STEM framework, the engineering component emphasizes applying scientific and mathematical concepts to design and implement solutions for real-world problems. In STEM–PjBL contexts, students actively engage in designing and producing tangible projects, thereby fostering creativity, problem-solving, and innovation (Lestari et al., 2024; Monika et al., 2023).

Equally important, the material is structured to support student-centered learning through collaborative exploration, reflection, and critical analysis. Activities are intentionally designed to foster learner autonomy and peer interaction while reinforcing core competencies in observation, classification, measurement, and inference. This design is expected to increase student engagement and promote deep learning, particularly in abstract topics such as invertebrate morphology and systematics (Mona & Rachmawati, 2023; Triwoelandari et al., 2023).

Validity and Practicality of the Teaching Material

Expert validation results indicated that the teaching material achieved a high level of content validity (98%), with strong ratings for content relevance (94%) and contextual alignment (100%). Experts recommended the inclusion of additional scaffolding features, such as glossaries and answer keys, to support varied learner needs. These suggestions were incorporated to increase accessibility and comprehension.

Practicality testing was conducted in three stages—individual, small group, and class-wide—to ensure that the material functioned effectively across different instructional settings (Hendra et al., 2022; Masdar & Lestari, 2021; Melanis et al., 2023). During the class-wide trial with 20 students, the material received an overall practicality score of 94.3%. High ratings were observed in visual appearance (92.75%), clarity of language (95.56%), material delivery (94.38%), and overall usefulness (94.5%). Students appreciated the real-world application of concepts, the clear structure, and the interactive elements of the modules.

Qualitative student feedback further highlighted that the material enabled them to engage in deeper analysis, increased their interest in fieldwork, and provided tools to visualize and make sense of complex biological data. These outcomes reinforce the importance of integrating hands-on, interdisciplinary learning within biological sciences education (Gaghunting & Bermuli, 2023).

Effectiveness in Enhancing Critical Thinking Skills

The effectiveness of the teaching material was evaluated using a pretest–posttest design analyzed with the Mann–Whitney U test, which revealed a statistically significant improvement in students' critical thinking skills ($p < 0.05$). Posttest results showed that 66.67% of students achieved the "very good" level and 33.33% reached the "good" level, with an overall average critical thinking score of 84%.

When measured against Ennis' five critical thinking indicators, the material was particularly effective in enhancing students' ability to provide simple explanations (91.75%) and to elaborate further (88.10%). Strategic skills—including inference, basic analysis, and logical planning—also demonstrated substantial gains, ranging from 76.19 to 83.33%. Although the lowest-performing skill, drawing conclusions, still yielded satisfactory results, its relative weakness indicates the need for targeted scaffolding in future revisions, such as guided reflection prompts or structured group discussions (Supeno et al., 2023; Dadelo, 2025).

These outcomes are consistent with previous findings, confirming that STEM-based learning enriched with explicit critical thinking strategies effectively strengthens higher-order cognitive skills (Adhelacahya et al., 2023). Overall, the results demonstrate that the STEM-based material not only improves content mastery but also significantly supports the development of higher-order thinking, aligning with the broader objectives of 21st-century education. This study further corroborates earlier evidence showing that STEM-based approaches enhance students' ability to analyze, evaluate, and draw conclusions from scientific information (Monika et al., 2023).

Conclusion

This study concludes that the integration of STEM-based instructional materials in the Invertebrate Zoology course significantly enhances undergraduate biology students' critical thinking skills. The developed materials demonstrated high levels of validity (98%) and practicality (94.3%) across individual, small group, and class-wide trials. Their effectiveness was evidenced by a statistically significant improvement in critical thinking performance, with 66.67% of students achieving the "very good" category and an average score of 84%. Among the five Ennis' critical thinking indicators, students achieved the highest mean score in "providing simple explanations" (91.75%) and "elaborating further" (88.10%), while the lowest score was observed in "drawing conclusions" (72.38%), indicating a need for further instructional support in that area. These findings reinforce the value of STEM-integrated approaches in supporting higher-order thinking and active learning through inquiry, measurement, and data analysis. The study recommends broader implementation of STEM-based teaching innovations to foster critical and reflective scientific thinkers in undergraduate biology education.

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Author Contributions

Conceptualization, K. and E.W.W.; methodology, software, formal analysis, investigation, resources, data curation, writing—original draft preparation, visualization, project administration, K.; validation, K., E.W.W., and A.R.; writing—review and editing, supervision, funding acquisition, E.W.W. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest
The authors declare no conflict of interest.

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