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ESD-Oriented Project-Based Differentiated Learning Model to Develop Critical Thinking Skills and Biodiversity Literacy

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Abstract

The 21st-century learning must integrate learning models that are appropriate to students' needs in facing the challenges of the times. This study aims to develop a project-based differentiated learning model oriented to Education for Sustainable Development (ESD) to improve students' critical thinking skills and biodiversity literacy. This model was designed by integrating a differentiation approach, project-based learning, and sustainability values. Validation by experts showed that this model has a high level of relevance and integration, with an average score of 4.7 on a scale of 5. Implementation of the model on high school students showed a significant increase in critical thinking skills (18.5 points) and biodiversity literacy (17.7 points) based on the results of the pre-test and post-test. The success factors of this model include contextualization of materials, differentiation approaches, and integration of sustainability values. These results indicate that this model is effective and relevant to be applied in biodiversity learning in high schools. This study recommends further development with a wider population to ensure the sustainability of its impact. The implementation of this model should be accompanied by comprehensive training for teachers to ensure a deep understanding of the principles of differentiation, project-based learning, and ESD values.

Keywords: Differentiated Learning; ESD Based Project; Critical Thinking Skills; Biodiversity Literacy; Expert Assessment

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INTRODUCTION

Biodiversity literacy has emerged as a vital competency in contemporary education, especially within the broader discourse of environmental sustainability and conservation. As defined by Prabowo et al. (2021), biodiversity literacy encompasses not only the knowledge of species and ecosystems but also an informed understanding of ecological interactions, sustainable resource management, and the human-environment interface. This depth of literacy is essential in equipping individuals with the knowledge and responsibility to address environmental degradation, notably in an era characterized by rapid biodiversity loss. The United Nations Environment Programme (UNEP, 2022) underscores the severity of the global biodiversity crisis, warning that over one million species are at risk of extinction due to anthropogenic pressures such as habitat destruction, pollution, and climate change. In this context, education has a strategic role in fostering ecological consciousness and catalyzing collective action.

Furthermore, the educational system has yet to fully embed pedagogies that develop the complex cognitive and affective dimensions of biodiversity literacy (Masemene & Msezane,

2021; Simionescu et al., 2020). Critical thinking a foundational 21st-century skill is similarly underdeveloped in many science classrooms, despite its strong linkage to ecological understanding. As Azrai et al. (2020) and Kusuma (2023) note, critical thinking enables learners to navigate and analyze complex environmental problems, fostering the capacity to make informed decisions and take responsible actions.

However, observational findings indicate that classroom practices often rely on uniform teaching methods that are less responsive to students' individual needs. Observations of project-based differentiated instruction reveal students' generative capacities in developing scientific literacy and critical thinking skills. These findings reinforce the importance of implementing active and collaborative learning strategies to achieve broader educational objectives, particularly regarding biodiversity and environmental issues. When supported by appropriate methods and innovative media, project-based learning has been shown to significantly enhance students' understanding of scientific concepts and their ability to address global challenges. This is consistent with Wahyuni (2020) findings, which highlight that the project-based learning process from observation to presentation was well-managed and significantly improved students' literacy skills.

Integrating critical thinking into environmental education is not only pedagogically sound but also vital in the context of sustainability education. Wibowo et al. (2024) demonstrate a significant correlation between critical thinking and environmental awareness, suggesting that enhancing one contributes meaningfully to the other. Furthermore, the ability to critically assess ecological claims, engage with evidence, and reflect on environmental ethics is central to shaping environmentally responsible citizens (Shutaleva, 2023). Yet, many current curricular models inadequately support this integration, either by prioritizing content over skills or by failing to provide experiential learning opportunities that would stimulate deeper reflection (Umar et al., 2024; Doup, 2018).

Education for Sustainable Development (ESD) offers a comprehensive framework for embedding sustainability into education systems. As outlined by UNESCO (2022), ESD promotes interdisciplinary learning, values education, and action-oriented pedagogies that cultivate environmental stewardship and global citizenship. ESD is not confined to ecological literacy; it encourages the development of holistic competencies cognitive, emotional, and behavioral that support sustainable development goals (Vioreza et al., 2023; Sterling, 2021). Specifically, in biodiversity education, ESD supports an integrated approach that transcends factual knowledge to emphasize systems thinking, ethical awareness, and participatory learning (Farliana & Hardianto, 2024; Álvarez et al., 2024). However, the implementation of ESD in classroom practice remains fragmented and often superficial due to curriculum constraints, teacher preparedness, and limited resources (Simionescu et al., 2020; Lubos, 2023).

To address these challenges, pedagogical innovations are necessary ones that not only align with ESD principles but also actively foster biodiversity literacy and critical thinking. Project-Based Learning (PjBL) is a well-established approach that engages students in investigating real-world problems through extended inquiry and collaborative projects (Genç, 2014). Numerous studies highlight PjBL's efficacy in developing problem-solving skills, deepening understanding of scientific content, and enhancing learner motivation (Dym et al., 2005; Barron & Darling-Hammond, 2020). In the context of biodiversity education, PjBL encourages direct interaction with environmental issues, enabling students to explore local ecosystems, propose solutions to conservation challenges, and reflect on their ecological footprint (Rahayu et al., 2025; Novak, 2017). Such experiential learning not only supports cognitive development but also emotional and ethical engagement with nature (Torralba-Burrial & Dopico, 2023).

Complementing this, Differentiated Instruction (DI) provides a framework for meeting the diverse needs of learners by adapting content, process, product, and learning environment according to student readiness, interest, and learning profiles (Tomlinson, 2017). Asriadi et al.

(2023), Kado et al. (2021), and Maulana et al. (2023) affirm that DI improves student engagement and achievement by offering personalized learning pathways. In diverse science classrooms, where students bring varying levels of prior knowledge and language proficiency, DI supports inclusion and equitable learning opportunities (Lee et al., 2019; Samsudi et al., 2024). Importantly, DI aligns with ESD's focus on learner-centeredness and transformative pedagogy, making it a valuable strategy in sustainability-oriented instruction (Rutt & Mumba, 2022). However, systemic barriers such as insufficient teacher training, large class sizes, and rigid curricula often hinder the effective application of DI in schools (Putra, 2023).

Although PjBL and DI have individually demonstrated potential in science education, few studies have explored their integration within an ESD framework, particularly in biodiversity learning. This represents a significant gap in the literature. Existing research often treats ESD, PjBL, and DI in isolation, missing the opportunity to examine their synergies and combined impact. For example, while Lemus (2019) illustrates how PjBL enhances inquiry-based learning in sustainability contexts, and Graaf et al. (2018) outline effective DI practices, there remains limited empirical exploration of how these methods can be jointly operationalized to advance ESD outcomes. Moreover, research on biodiversity education models that explicitly integrate these three dimensions ESD, PjBL, and DI is notably scarce in secondary science settings, particularly in regions facing urgent biodiversity threats.

The integration of ESD, PjBL, and DI presents both opportunities and challenges. On one hand, such an integrated model can foster holistic competencies critical thinking, ecological awareness, collaboration, and adaptability that are essential for navigating sustainability challenges (Sluijs et al., 2024; Amin et al., 2020). On the other hand, implementing such a model requires careful alignment with curriculum standards, teacher capacity-building, and the development of robust assessment tools. For instance, while Enriquez-Andrade (2019) and Oliver et al. (2019) highlight the potential of inquiry-based approaches aligned with ESD, they also emphasize the epistemological and institutional barriers teachers face. Similarly, Malinga et al. (2021) identify gaps in DI application due to inadequate training, which may limit educators' ability to respond to student diversity effectively.

The present study responds to these gaps by developing and testing an instructional model that integrates Project-Based Learning, Differentiated Instruction, and Education for Sustainable Development principles to enhance biodiversity literacy and critical thinking among secondary school students. Unlike prior models that address these pedagogies in isolation, the proposed model seeks to synthesize them into a coherent, contextually relevant, and pedagogically robust framework. This model is grounded in the understanding that students learn best when instruction is both personally meaningful and socially relevant principles central to both DI and ESD and when they are actively engaged in constructing knowledge through authentic inquiry, as advocated by PjBL (Genç, 2014; Sterling, 2021).

In doing so, this study not only contributes to the empirical evidence base on ESD pedagogy but also offers a conceptual innovation that bridges theoretical and practical domains. The model is particularly designed to address limitations identified in biodiversity education: the lack of student engagement (Doup, 2018), complexity of ecological concepts (Umar et al., 2024), teacher confidence and preparation (Lindemann-Matthies et al., 2011), and the fragmented nature of curriculum design (Rammou et al., 2023). It also seeks to fill the pedagogical void by equipping teachers with tools and strategies to simultaneously manage content differentiation, project facilitation, and sustainability integration.

Based on the above problem, this study aims to integrate differentiated instruction with project-based learning within the ESD framework to enhance students' critical thinking skills and biodiversity literacy. This approach is expected to meet the demands of modern education and address the challenges of 21st-century learning.

METHOD

Research Design and Overview

This study employed a multi-phase design-based research approach focused on the development, validation, and limited implementation of an innovative instructional model integrating Education for Sustainable Development (ESD), Project-Based Learning (PjBL), and Differentiated Instruction (DI). The purpose of the model was to enhance students' critical thinking skills and biodiversity literacy at the secondary education level. The research process consisted of five interrelated phases: (1) needs assessment, (2) model development, (3) expert validation, (4) limited implementation, and (5) data analysis.

Needs Identification

To inform the initial design of the instructional model, a qualitative needs assessment was conducted through structured interviews and document analysis. Participants included 15 biology teachers, 50 students, and 3 school principals from three urban high schools. Interviews focused on pedagogical challenges, students' learning diversity, and the gaps in environmental and biodiversity education practices. In addition, curricular documents and teaching materials were reviewed to identify the extent of integration of sustainability and differentiated pedagogy.

Findings from this phase confirmed several limitations: lack of contextual and experiential learning activities, uniform teaching methods not aligned with learner variability, and insufficient emphasis on critical thinking and biodiversity literacy. These insights informed the theoretical grounding and structural components of the instructional model.

Model Development

Based on the identified needs and supported by relevant pedagogical frameworks, a project-based differentiated learning model oriented to ESD was designed. The model was structured into three main components:

1. **Project Planning**: Students were guided to identify real-life biodiversity issues in their local environments (urban species decline, plastic waste impacts on ecosystems). Teachers facilitated brainstorming sessions, allowing project selection based on students' interests and readiness levels a key DI principle.
2. **Implementation Guidelines**: Each project was implemented in small groups, using tiered tasks and flexible grouping to accommodate different learning profiles. Students engaged in research, field investigations, community surveys, and eco-design solutions.
3. **Evaluation of Learning Outcomes**: Assessments were multi-modal and included individual reflections, group presentations, and biodiversity action proposals. Rubrics were developed to assess critical thinking and biodiversity literacy indicators.

The instructional activities were mapped to 21st-century competencies, sustainability learning outcomes, and the local high school science curriculum, ensuring curricular alignment.

Expert Validation

To determine the validity and feasibility of the model, a validation process was conducted involving three experts each with expertise in education, ESD, and biodiversity science. Experts reviewed the model documentation using a structured instrument based on a 5-point Likert scale. The main components assessed in the feasibility of the model are content relevance, method integration, and development potential. These results confirm the strong alignment of the model with both theoretical and practical educational goals.

In addition to the numerical data, qualitative feedback from the experts was also integrated into model refinement. Comments focused on enhancing the specificity of biodiversity examples, increasing scaffolding tools for differentiated tasks, and ensuring sustainability themes were embedded throughout.

Limited Implementation

The revised model was implemented on a limited scale in three science classes (n = 90 students) across the participating schools. The implementation spanned six weeks, during which students participated in a series of biodiversity-themed project activities. To measure the model's impact, students completed a pre-test and post-test assessing both critical thinking skills and biodiversity literacy. The critical thinking test was adapted from validated instruments in environmental education (Uddin, 2021; Shutaleva, 2023), and aligned with the indicators of higher-order thinking, including analyzing arguments, drawing inferences, interpretation, evaluation, and decision-making. Whereas The biodiversity literacy assessment was developed based on validated constructs from Efe & Efe (2022), including definition and importance of biodiversity, utilization and conservation strategies, and understanding human impact on ecosystems.

These instruments were subjected to expert review to ensure content validity, following the Content Validity Index (CVI) methodology (Adegoye et al., 2023; Karaman et al., 2023). The I-CVI for each item exceeded 0.80, confirming acceptable levels of agreement among expert raters.

Data Analysis

The data in this study were analyzed using a quantitative inferential statistical approach, focusing on testing the effectiveness of a project-based learning model integrated with the principles of Education for Sustainable Development (ESD) and Differentiated Instruction (DI). To measure the improvement in students' critical thinking skills and biodiversity literacy before and after the implementation of the model, a paired sample t-test was employed. The paired sample t-test is a commonly used statistical method in quasi-experimental studies and educational interventions due to its ability to compare two related sets of data, such as the pre-test and post-test scores from the same group of participants (Rahayu et al., 2024; Sudirman, 2023; Putri et al., 2023).

RESULTS AND DISCUSSION

The ESD-oriented project-based differentiated learning model has proven effective in improving students' critical thinking skills and biodiversity literacy. This approach offers an innovative solution for biodiversity learning that is relevant to the demands of 21st century education. It is hoped that further research can test this model in a broader context and with a more diverse student population. The validation results show that this model has a high level of feasibility in the following aspects.

Table 1. Expert Validation of Learning Models

Assessment Aspects	Average score
Content Relevance	4,7
Method Integration	4,5
Development Potential	4,8

Pre-Test and Post-Test Results

The improvement of students' abilities was measured through pre-test and post-test. The following graph shows the improvement in average scores on critical thinking skills and biodiversity literacy.

Figure 1 illustrates on clearly demonstrates that the learning model had a substantial and balanced impact on both cognitive and ecological literacy domains. The improvements not only validate the effectiveness of the model in enhancing academic performance, but also underscore its potential for fostering integrated competencies aligned with Education for Sustainable Development (ESD) goals. For clarity and can be seen in Table 2.

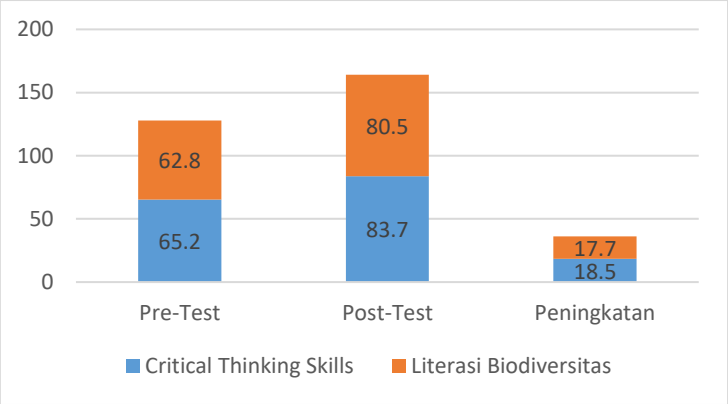

Figure 1. Average Improvement of Student Scores

Table 2. Increase in Critical Thinking Skills and Biodiversity Literacy Scores

Aspect	Pre-Test	Post-Test	Improvement
Critical Thinking Skills	65.2	83.7	18.5
Literasi Biodiversitas	62.8	80.5	17.7

The implementation of the ESD-oriented project-based differentiated learning model has shown very promising results in improving students' critical thinking skills and biodiversity literacy. A significant increase of 18.5 points in critical thinking skills and 17.7 points in biodiversity literacy indicates the effectiveness of the approach used. This shows that the integration of project-based learning, differentiation, and ESD values is able to create a conducive learning environment for the development of high-level skills. Likewise, the results of the paired sample t-test show that there is a positive influence on critical thinking skills and biodiversity literacy. This positive influence is in the form of an increase in each individual's score on each measured ability (Table 3).

Table 3. The results of the paired sample t-test

Aspect	df	Score t	Sign (2-tailed)
Critical Thinking Skills	89	-61.10	0.000
Literasi Biodiversitas	89	-69.54	0.000

The success of the ESD-oriented Project-Based Differentiated Learning (PjBDL) model in enhancing students' critical thinking skills and biodiversity literacy cannot be separated from its robust and deliberate design particularly its contextualized learning materials, flexible instructional strategies through differentiated instruction (DI), and a strong emphasis on Education for Sustainable Development (ESD) values. These three foundational pillars create a coherent pedagogical framework that responds to the diverse needs of learners, aligns with 21st-century educational goals, and addresses pressing environmental concerns in a locally relevant manner.

One of the key factors behind the model's success lies in the strong contextualization of learning materials and activities, making educational content more meaningful and engaging. Students were not simply passive recipients of abstract knowledge; rather, they engaged in projects that were grounded in real environmental issues from their own communities, such as local biodiversity mapping, waste analysis, or sustainability audits. This approach increases the salience of learning, as it helps students perceive the relevance of classroom instruction in their everyday lives. Barron & Darling-Hammond (2020) emphasize that when learning is grounded in the local context and based on real-world challenges, students are more likely to engage

critically and creatively. Similarly, Chang et al. (2024) found that authenticity in learning tasks enhances retention and motivation. In this study, students did not merely learn about biodiversity conceptually they applied their knowledge in real situations, thus internalizing key ecological principles and cultivating a deeper sense of environmental responsibility.

The project-based learning (PjBL) element of the model was instrumental in achieving this level of engagement and cognitive development. A substantial body of literature supports the role of PjBL in developing higher-order thinking skills (Sungkono & Ekaputra, 2023; Situmorang et al., 2022). In this study, students demonstrated improved abilities in reasoning, inference, analysis, and evidence-based decision-making through collaborative project work. Tasks such as evaluating the effects of urbanization on local fauna or designing eco-literacy campaigns required not only content knowledge but also the capacity for critical engagement. Wibowo et al. (2024) and Utomo et al. (2023) confirm that PjBL enhances critical thinking by encouraging learners to navigate interdisciplinary problems and seek out solutions independently or in teams. Komara et al. (2023) highlight the social dimensions of PjBL, where dialogue, negotiation, and collaboration foster deeper cognitive processing dynamics that were clearly present in the group-based projects conducted in this research.

Complementing this, the differentiated instruction (DI) component ensured that all students, regardless of their initial ability or learning preferences, could engage meaningfully with the material. DI strategies used in the model included flexible grouping, tiered tasks, choice boards, and personalized project themes. These methods were designed to respect student variability and promote equitable access to learning. According to Asriadi et al. (2023), DI significantly improves student outcomes in diverse classrooms by matching instruction to students' readiness, interest, and learning profiles. In this study, the implementation of DI resulted in increased student motivation and engagement, consistent with findings by Krishan & Al-Rsa'i (2023) and Marlina et al. (2019), who observed that DI fosters both cognitive growth and emotional investment in learning. Additionally, although the model's use of technology was not extensive, digital tools were employed for reflection and presentation, aligning with Chen & Wang (2015) who argue that technology-enhanced DI can improve accessibility for different learner types.

These instructional strategies were brought together within a framework grounded in Education for Sustainable Development (ESD). The model did not treat sustainability as an add-on or abstract theme; rather, it infused ESD values throughout the curriculum—promoting systems thinking, environmental ethics, global-local interconnectedness, and active citizenship. This aligns with UNESCO's (2022) vision of ESD as a transformative pedagogy that develops competencies needed for addressing complex sustainability issues. Students in the study explored socio-ecological systems, engaged with conservation ethics, and developed a sense of responsibility for local biodiversity. The work of Vioreza et al. (2023) and Sterling (2021) further affirms the importance of these elements in fostering sustainability literate citizens. Moreover, the model's use of experiential learning methods such as outdoor observations, community investigations, and biodiversity audits resonates with findings from Prabowo et al. (2021), Mo'in & Sapaat (2024), and Paradise & Bartkovich (2021), who argue that hands-on, sensory-rich activities are particularly effective in promoting biodiversity literacy and stewardship.

Quantitative data from this study reflect holistic student development across both cognitive and affective domains. The improvement in critical thinking skills from an average pre-test score of 65.2 to a post-test score of 83.7 demonstrates significant cognitive gains in reasoning, evaluation, and problem-solving. Similarly, biodiversity literacy scores rose from 62.8 to 80.5, reflecting improved conceptual understanding and ecological awareness. These findings are consistent with research by Amin et al. (2020) and Guna et al. (2023), who assert that integrative, student-centered pedagogies are essential for developing sustainability related competencies. Moreover, the model aligns with constructivist learning theories, which

emphasize the importance of learner autonomy, reflective inquiry, and contextual relevance all key features of both PjBL and DI.

When positioned within the broader literature, this study stands out for its integration of three pedagogical frameworks PjBL, DI, and ESD into a single cohesive model. Most prior studies have examined these approaches in isolation. For instance, Utomo et al. (2023) focus on PjBL alone, while Rutt & Mumba (2022) explore DI within environmental science. The unique contribution of this study lies in showing how the synergy of these three approaches yields greater outcomes than when applied separately. Research by Wahyu et al. (2023) and Syukri et al. (2021) suggests that the effect sizes of single-modality interventions are often moderate, whereas the combined approach in this study resulted in more substantial learning gains.

Nevertheless, certain limitations should be acknowledged. First, the sample size was relatively small and drawn from a limited geographic area, which may constrain the generalizability of the findings. Expanding the study across different regions and school types would allow for broader validation. Second, the absence of a control group limits the ability to make definitive causal claims. Incorporating a quasi-experimental design in future research could address this issue. Third, while the pre- and post-tests were validated and statistically robust, they primarily captured short-term cognitive outcomes. Including qualitative methods such as interviews or reflective journals could provide richer insights into student experiences and long-term impact. Finally, the study assessed only immediate post-intervention outcomes. A longitudinal follow-up would be necessary to determine the persistence of learning gains and the influence on students' future behaviors and attitudes toward sustainability. These critiques echo those raised by Pauw et al. (2015).

Despite these limitations, the study holds several important practical and theoretical implications. Theoretically, it contributes to ongoing discussions about the compatibility and complementarity of differentiated learning and sustainability education. Drawing from Setti & Azeiteiro (2016) and Rauch (2015), the study shows that personalized instruction does not conflict with collective sustainability goals; rather, it can be a pathway to more inclusive, equitable, and meaningful engagement with environmental issues. In practice, the model offers a scalable blueprint for schools, teacher education programs, and policy makers. Key elements such as scaffolded project planning, flexible instruction, and sustainability framing can inform curriculum development, professional development, and instructional design across diverse contexts.

The findings also suggest that investing in teacher capacity-building is crucial for effective implementation. As noted by Smets & Struyven (2020), the success of differentiated approaches relies heavily on teacher readiness to assess, plan, and adapt instruction continuously. This is especially relevant when adopting interdisciplinary, student-driven models like PjBDL, which require educators to be curriculum designers, facilitators, and reflective practitioners. Therefore, future iterations of this model should be accompanied by structured professional development programs focused on PjBL design, DI strategies, and ESD principles.

CONCLUSION

The study demonstrates that the ESD-oriented Project-Based Differentiated Learning (PjBDL) model is effective in enhancing students' critical thinking skills and biodiversity literacy. The model integrates three key pedagogical approaches Education for Sustainable Development (ESD), Project-Based Learning (PjBL), and Differentiated Instruction (DI) to create a holistic, student-centered learning experience. The implementation of the model resulted in significant improvements in students' critical thinking (18.5 points increase) and biodiversity literacy (17.7 points increase), validated by both expert assessments and statistical analyses. The success factors identified include the contextualization of learning materials to

local environmental issues, adaptive instructional strategies catering to diverse learners, and a strong focus on sustainability values. This study contributes to the existing literature by bridging theoretical frameworks with practical application, offering a robust and replicable instructional model for secondary education settings.

RECOMMENDATION

Future research should focus on implementing the PjBDL model on a larger and more diverse scale to ensure generalizability across different contexts and student populations. It is recommended that comprehensive teacher training programs be developed and integrated alongside the model's rollout, focusing on PjBL design, DI strategies, and ESD principles to ensure effective implementation. Additionally, longitudinal studies should be conducted to assess the long-term impact of the model on students' critical thinking, biodiversity literacy, and environmental behavior. Further refinement of assessment tools especially those capturing qualitative insights, such as reflective journals and interviews would enrich understanding of students' learning experiences. Lastly, collaboration between schools, communities, and environmental stakeholders should be strengthened to enhance the contextual relevance of learning and promote real-world engagement with biodiversity issues.

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