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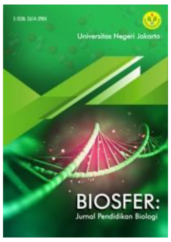

Developing and validating a project-based environmental education (PjBEE) model to enhance sustainability competencies

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ABSTRACT

The enhancement of students' sustainability competencies remains a critical challenge in higher education. While project-based learning approaches have been effective in improving students' problem-solving and collaboration abilities, their capacity to address complex environmental and sustainability issues is still limited. To overcome these limitations, this study developed and validated a Project-Based Environmental Education (PjBEE) model that integrates project-based learning with sustainability-oriented education. Employing a Research and Development (R&D), this study aimed to determine the model's validity, practicality, and effectiveness in enhancing students' sustainability competencies. The PjBEE model was implemented in environmental education courses and structured around six stages: Inquiring, Collaborating, Decision Making, Digital Action Planning, Creating Artifacts, and Action. Research instruments included expert validation sheets, observation sheets, student response questionnaires, and sustainability competency tests. The validation results confirmed that the PjBEE model met the criteria of high validity, feasibility, and practicality. Implementation findings demonstrated positive student engagement and significant improvement in sustainability competencies particularly in systems thinking, collaboration, strategic planning, and problem-solving. Therefore, the PjBEE model can serve as a pedagogically sound and empirically supported framework for integrating sustainability education into higher education curricula, particularly in biology teacher education programs.

INTRODUCTION

Sustainability competencies encompass a set of skills, knowledge, and attitudes crucial for tackling environmental, social, and economic challenges. These competencies are integral to fostering a sustainable future and are prioritized in educational frameworks aimed at promoting sustainable development. They include critical thinking, systems thinking, ethical responsibility, and the ability to envision and implement sustainable solutions (Eizaguirre et al., 2019; Nasr-Azadani et al., 2023; Valdes-Ramirez et al., 2024; Xiao et al., 2025). Developing sustainability competencies for students is crucial in addressing global environmental, social, and economic challenges. These competencies encompass a broad range of skills, including systems thinking, interdisciplinary collaboration, and the application of scientific and technical knowledge to solve complex problems (Afy-Shararah et al., 2024; Vanoye-Garcia et al., 2024). Higher education institutions play a pivotal role in equipping students with these competencies, which are essential for promoting sustainable development and achieving the Sustainable Development Goals (SDGs) (Eizaguirre et al., 2019; Afy-Shararah et al., 2024; Yadav, 2025). Embedding sustainability education into higher education enables students to understand the economic aspects of sustainable development, allowing them to contribute to a sustainable and innovative economy (Eizaguirre et al., 2019; Zwolińska et al., 2022). Furthermore, it enhances students' awareness and skills necessary for environmental protection, which is critical in addressing urgent issues such as climate change, resource scarcity, and environmental degradation (Zwolińska et al., 2022; Yadav, 2025). Integrating sustainability into curricula also fosters social responsibility and ethical commitment, preparing students to address social justice issues and promote equity in society (Eizaguirre et al., ; Grant-Smith et al., 2023; Lemke et al., 2023).

Despite its importance, the integration of sustainability into higher education still encounters several challenges. These include rigid curricula, resistance to institutional change, and disparities in funding and resources (Afy-Shararah et al., 2024; Yadav, 2025). The integration of sustainability into higher education is widely recognized as crucial for addressing the interconnected environmental, social, and economic challenges faced by contemporary societies. Nevertheless, this integration continues to be hindered by several persistent structural and institutional barriers. One major obstacle lies in the rigidity of existing curricula. Many higher education institutions struggle to embed sustainability principles within established academic frameworks due to entrenched pedagogical traditions and strong disciplinary boundaries (Gale et al., 2015; Leal Filho et al., 2017; Weldemariam et al., 2025). The persistence of traditional technical paradigms and a reluctance to undertake curricular reforms further exacerbate this challenge (Sabri, 2025). Additionally, resistance to institutional change remains a pervasive issue. Universities have historically prioritized academic excellence and research productivity over sustainability initiatives, creating tensions between sustainability objectives and institutional missions (Gale et al., 2015; Thakur et al., 2025). In many cases, insufficient faculty motivation and engagement further complicate the process of mainstreaming sustainability into academic culture (Brahm & Kuhner, 2019). Another critical barrier relates to disparities in funding and resources. Financial constraints, including limited allocations for sustainability programs and the substantial costs associated with implementing sustainable practices, significantly impede progress (Thakur et al., 2025; Núñez, 2025; Basheer et al., 2025). Moreover, these resource gaps extend beyond funding to include inadequate technological infrastructure and institutional support for sustainability-oriented education (Tarraya et al., 2025). Collectively, these barriers highlight the complexity of achieving systemic transformation toward sustainability within higher education. In addition, educators may lack confidence and sufficient proficiency in embedding sustainability within their teaching practices, thereby limiting the development of sustainability competencies among students (Grant-Smith et al., 2023; White, R. M et al., 2025). Students' attitudes and expectations also significantly influence the effectiveness of sustainability education, and aligning educational strategies with students' perspectives has been shown to enhance its quality and outcomes (Maiorescu et al., 2020; Kocot, M et al., 2024). To address these challenges, effective approaches are required that not only provide theoretical knowledge but also practical experiences. For example, educational platforms that simulate real production environments serve as valuable tools to bridge academia with industry while fostering competency development (Afy-Shararah et al., 2024). Likewise, engaging students in real-world problems through project-based learning (PBL) enhances critical thinking, collaboration, and technical proficiency, thereby strengthening sustainability competencies (Vanoye-Garcia et al., 2024). Such approaches also encourage reflective practices, enabling students to confront their assumptions and adopt new perspectives that drive transformative change (Xiao et al., 2025).

In the Indonesian higher education context, the integration of sustainability competencies has increasingly become a strategic priority following the implementation of Permendikbudristek No. 53 of 2023 concerning learning outcomes and the Merdeka Belajar–Kampus Merdeka (MBKM) framework. This policy shift emphasizes the importance of embedding sustainability into the curriculum to enhance students' competencies in critical thinking, scientific argumentation, and academic communication, which are essential for addressing environmental and social challenges (Mulyaningsih et al., 2025)1. Additionally, the MBKM framework encourages innovative educational practices, such as project-based learning and interdisciplinary approaches, to foster sustainability awareness and competencies among students (Faizah et al., 2025). This strategic focus aligns with global trends in higher education, where the integration of sustainability principles is seen as crucial for preparing students to contribute effectively to sustainable development goals (Idoiaga Mondragon et al., 2023).

Project-Based Learning (PjBL) has become one of the most widely adopted educational approaches, emphasizing active and experiential learning through real-world projects. While PjBL has been praised for enhancing student motivation, collaboration, and problem-solving skills, it demonstrates notable weaknesses in the domain of sustainability education. One significant limitation is its inconsistent integration of sustainability competencies. Although PjBL aims to address complex, real-world problems, it often falls short in systematically embedding sustainability challenges and promoting pro-environmental behaviors (Brundiers & Wiek, 2013; Schoch et al., 2025). For instance, while PjBL can encourage students to engage with sustainability topics, it lacks a structured framework to ensure that such engagements translate into long-term sustainable practices. Furthermore, PjBL courses frequently fail to fully incorporate critical sustainability learning objectives and participatory research education, which results in a lack of comprehensive sustainability competencies among students (Brundiers & Wiek, 2013; Bramwell-Lalor et al., 2020). In many cases, the projects designed in PjBL are derived from basic academic competencies rather than actual industry or community needs, producing outputs that are less practical or marketable and thereby reducing the real-world applicability of the learning experience (Sudjimat, 2016).

While Project-Based Learning (PjBL) provides an effective framework for fostering student engagement, collaboration, and experiential learning. However, its limited focus on sustainability-oriented goals indicates the need for integration with pedagogical approaches that emphasize environmental ethics and responsibility. This integration is essential to address complex environmental issues and promote sustainable practices in education (Singha & Singha, 2024; Moreira & Marques, 2025; Quyen et al., 2025). The Environmental Education Model (EEM), in contrast, emphasizes the development of environmental consciousness and pro-environmental behavior (Stanišić et al., 2023, Wu et al., 2024; Zhao et al., 2024).

The Environmental Education Model (EEM) plays a crucial role in raising environmental awareness and promoting pro-environmental behaviors among students. This model is specifically designed to enhance individuals' understanding of environmental issues and foster a sense of responsibility towards the environment. While EEM effectively increases awareness, it often falls short in encouraging collaborative and problem-solving skills that are indispensable for addressing complex environmental challenges. EEM primarily seeks to increase environmental knowledge and awareness, and studies consistently show that environmental education positively influences students' environmental concern and their willingness to engage in environmentally friendly behaviors (Sharma et al., 2023; Al-Ghazo & Alshboul, 2024; Gebreki dan & Gebremedhin, 2024). This heightened awareness is fundamental for fostering a generation that values and protects the environment.

Nevertheless, despite its success in cultivating awareness, EEM does not sufficiently promote the collaborative and problem-solving dimensions of learning. Many environmental education practices are still limited to theoretical approaches and awareness campaigns, which rarely engage students in practical, hands-on problem-solving activities (dos Santos et al., 2021; Guevara-Herrero et al., ; Pérez-Martín et al., 2024). This limitation constrains the development of critical thinking and teamwork skills, both of which are essential for translating environmental concern into effective environmental action. To address this gap, scholars have increasingly called for a transformative perspective in environmental education that emphasizes critical reflection, decision-making, and the integration of social justice within environmental issues (Guevara-Herrero et al., 2024; Pérez-Martín et al., 2024). By embedding these perspectives, students are better positioned to approach environmental problems holistically and collaboratively. In line with this, effective environmental education should be grounded in interdisciplinary and participatory activities that encourage students to work together on real-world problems. Successful initiatives in this direction include collaborative projects, experiential learning, and community engagement, all of which have demonstrated positive outcomes in fostering problem-solving skills and environmental stewardship (Santos et al., 2018; Mello et al., 2021; Singh, 2026).

In this regard, while PjBL provides opportunities for experiential and collaborative learning, yet lacks consistent integration of sustainability competencies, and EEM fosters strong environmental awareness, yet falls short in building problem-solving and teamwork skills, there emerges a clear need for an integrative pedagogical model. Such a model should bridge the strengths of PjBL and EEM to create a more comprehensive and transformative approach that equips students with both the knowledge and competencies required for sustainability education. Given these limitations, there is a pressing need to design a more integrative pedagogical approach that combines the strengths of PjBL and EEM. Thus, rather than treating PjBL and EEM as separate variables, this study seeks to integrate their complementary strengths. By combining the inquiry-driven, participatory nature of PjBL with the value-oriented and ecological dimensions of EEM, the Project-Based Environmental Education (PjBEE) model is conceptualized to holistically strengthen students' sustainability competencies in higher education contexts. Project-Based Environmental Education (PjBEE) emerges as an innovative model that addresses this gap by merging the experiential, collaborative, and problem-solving orientation of PjBL with the environmental awareness and value-driven foundation of EEM. As a hybrid model, PjBEE seeks to empower students' sustainability competencies more holistically, encompassing cognitive, affective, and behavioral dimensions. Through structured projects rooted in real environmental issues, students not only gain practical skills in research, teamwork, and critical thinking but also cultivate environmental ethics and long-term commitment to sustainable practices. In this way, PjBEE is positioned as a transformative framework that prepares students to act as change agents in addressing global sustainability challenges. This research aims to develop a Project Based Environmental Education (PjBEE) model that is valid, practical, and effective in empowering sustainability competencies. The development of sustainability competencies in this study is contextually embedded within the Environmental Education course offered to pre-service biology teachers at Tidar University. This course is positioned in the third semester as a compulsory subject within the Biology Education Study Program, aiming to strengthen students' comprehension of environmental systems, ecological balance, and sustainable practices in both theory and practice.

METHODS

The indicators of sustainability competencies measured in this research were formulated to reflect the essential abilities required for sustainable action in higher education learning contexts. These indicators consist of seven core aspects: (1) Systems Thinking Competency, referring to the ability to identify relationships and interdependencies among ecological, social, and economic dimensions of environmental problems; (2) Anticipatory Competency, representing the ability to foresee and assess potential future impacts of environmental changes; (3) Normative Competency, which emphasizes the integration of ethical reasoning and sustainability values in making judgments; (4) Strategic Competency, describing the capacity to design and implement effective strategies to achieve sustainable outcomes; (5) Collaboration Competency, highlighting the ability to work cooperatively across disciplines and with community partners to address sustainability challenges; (6) Self-Awareness Competency, concerning the understanding of one's role, responsibility, and values in sustainable decision-making; and (7) Problem-Solving Competency, focusing on the application of analytical and creative approaches to resolve real-world sustainability issues.

Research Design

This research employs a Research and Development (R&D) design, specifically aimed at developing the Project-Based Environmental Education (PjBEE) model to empower students' sustainability competencies. The model's development refers to the ADDIE instructional design model (Branch, 2009), which consists of five systematic stages. 1) The Analysis phase focuses on identifying learning needs to develop students' sustainability competencies. 2) The Design phase involves planning the learning model based on the results of the analysis, which includes designing the PjBEE syntax, learning scenarios, and instruments for evaluation. 3) The Development phase emphasizes the creation of the PjBEE prototype, expert validation, and revisions through iterative formative evaluations, such as self-evaluation and expert review. 4) The Implementation phase tests the model in actual classroom settings to examine its practicality and applicability in empowering sustainability competencies. Implementation is carried out in two stages, namely a one-to-one trial and a small group trial. 5) The Evaluation phase assesses the validity, practicality, and effectiveness of the developed model through a pretest-posttest design, comparing students' competencies before and after the intervention. This design ensures that the developed PjBEE model is systematically validated and empirically tested to meet the goals of sustainability education. The research design used in this study to assess the effectiveness of the developed PjBEE model is a one-group pretest-posttest design, which tests at the beginning and end of learning in one group.

Population and Samples

The participants in this study were exclusively students from Tidar University, Indonesia. The sample comprised 40 students enrolled in environmental education courses.

Instrument

This study employed four research instruments designed to evaluate the validity, feasibility, and effectiveness of the Project-Based Environmental Education (PjBEE) model in fostering sustainability competencies among pre-service biology teachers (Jumrodah et al., 2019; Paristiowati et al., 2022; Rasis et al., 2023; Agustira et al., 2025). The feasibility of the model was measured through implementation observations and lecturer readiness during one-to-one and small-group trials. The PjBEE model validation sheet consisted of 28 items, focusing on syntactic feasibility, alignment of learning objectives, material relevance, and clarity of implementation steps, which were assessed by three expert validators. The observation sheet, comprising 15 items, was used by three observers during the classroom implementation to evaluate student engagement, lecturer management, and conformity between the observed practice and the model's design. Furthermore, the student response questionnaire contained 25 items measuring students' perceptions, satisfaction, and engagement toward the PjBEE-based learning experience. Finally, the sustainability competencies test consisted of 21 items distributed across seven dimensions to measure the extent to which the PjBEE model enhanced students sustainability competencies. The test was administered twice: as a pre-test before the implementation of the PjBEE model and as a post-test after the learning intervention. The comparison of pre-test and post-test results provided empirical evidence of the model's effectiveness in developing sustainability competencies among pre-service teachers.

Data Analysis Techniques

The qualitative data collected during the initial study phase were evaluated descriptively. The findings encompassed the continuous learning process associated with students' sustainability abilities and the necessity for the development of the PjBEE model. The quantitative data collected were computed based on students' achievement scores for each competency variable, utilizing Formula (1). The validation results of the PjBEE model were assessed for validity and reliability by experts. The criteria for product validity (as outlined in Formula (2) and Table 1) and the interpretation criteria for the intra-class correlation coefficient (presented in Table 2) were analyzed.

$$P = \frac{SC}{SM} \times 100 \qquad (1)$$

Information:
P = Achievement
SC = Achievement Score
SM = Maximum Score

$$\text{Expert Scoring} = \frac{Total\ Score\ Obtained \times 100}{Max\ Score \times Number\ of\ assesment\ aspects} \qquad (2)$$

Table 1.
Product Validity Criteria

Interval Score (%)	Category	Interpretation
85-100	Very Valid	The product can be used without revision
70 – 84	Valid	The product can be used with minor revision
55 – 69	Quite Valid	The product needs revision before implementation
40 – 54	Less Valid	The product is not recommended, major revision needed
< 40	Invalid	The product cannot be used

(Adapted from Tegeh et al. (2014)

* For content material, the validity level must be 100%.

The classification of product validity levels (Table 1) follows the interpretation model commonly applied in educational design research (Plomp, 2013; van den Akker et al., 2012). Each range is treated as an inclusive upper-bound interval; for instance, a validity score of 84.31% is categorized as "Valid," while 85.00% or higher is "Very Valid." Fractional results were rounded to two decimal places to ensure consistency. This approach aligns with standard practices in R&D-based educational model validation to ensure transparency and replicability of evaluation results.

Assess the consistency and reliability of the PjBEE model evaluation by the validator through inter-rater reliability (IRR) analysis. Inter-rater reliability refers to the consistency of agreement among different raters. The IRR offers a score that reflects the degree of consensus or agreement among experts. The IRR coefficient is denoted by the intra-class correlation coefficient (ICC). Data analysis utilized the SPSS 23 for Windows program to derive the ICC values, which were subsequently interpreted based on reliability classification criteria.

Table 2.
Interpretation Criteria for Intra-Class Correlation Coefficient (ICC)

ICC Value	Reliability Category	Interpretation
< 0.50	Poor	Low agreement between raters, unacceptable reliability
0.50 – 0.75	Moderate	Moderate agreement, acceptable for exploratory research
0.76 – 0.90	Good	High agreement, reliable for most research purposes
> 0.90	Excellent	Very high agreement, strongly reliable

(Source: Koo & Li, 2016)

The implementation sheet for the PjBEE learning model components and student responses was calculated using assessment formula (3), followed by an evaluation of the practical feasibility criteria for the product (Table 3).

$$\text{Scoring} = \frac{Total\ Score\ obtained\ x\ 100}{Max\ Score\ x\ number\ of\ assesment\ aspects} \qquad (3)$$

Table 3.
Product Practicality Criteria

Interval Score (%)	Category	Interpretation
85-100	Very Valid	The product can be used without revision
70 – 84	Valid	The product can be used with minor revision
55 – 69	Quite Valid	The product needs revision before implementation
40 – 54	Less Valid	The product is not recommended, major revision needed
< 40	Invalid	The product cannot be used

(Adapted from Tegeh et al. (2014)

The classification of product validity levels (Table 3) follows the interpretation model commonly applied in educational design research (Plomp, 2013; van den Akker et al., 2012). Each range is treated as an inclusive upper-bound interval; for instance, a validity score of 84.31% is categorized as "Valid," while 85.00% or higher is "Very Valid." Fractional results were rounded to two decimal places to ensure consistency. This approach aligns with standard practices in R&D-based educational model validation to ensure transparency and replicability of evaluation results. Inferential analysis examines the impact of learning models on variables related to research skills. The analysis employed a paired sample t-test. Prerequisite tests, such as normality and homogeneity tests, are conducted before paired sample t-tests.

RESULTS AND DISCUSSION

The research findings are presented in alignment with the stages of the ADDIE Development Model: (1) Analyze, (2) Design, (3) Development, (4) Implementation, and (5) Evaluation.

(1) Analyze

The analysis stage was conducted to identify learning needs in order to develop students' sustainability competencies. The results of the preliminary research, which were analyzed descriptively, showed that all sustainability competency indicators obtained an average score of 49.97, which can be categorized as low. In addition, the standard deviation analysis results showed an average value of

17.03, indicating a fairly large spread of data around the average value. This condition indicates that there are significant differences in results between respondents, so that student sustainability competencies are not yet evenly distributed and tend to vary between individuals. Overall, these findings reinforce the urgency of developing a learning model that can improve and even out students' sustainability competency achievements. Details of the descriptive analysis results can be seen in Table 4.

Preliminary research was also conducted to identify various obstacles experienced by students in applying project-based learning methods. Descriptive analysis results show that, in general, all learning obstacle indicators are in the low category. The average score for each indicator is around 2.326, with a standard deviation of 0.45, indicating that the diversity of student responses is in the low to moderate category. However, there were two indicators with the lowest average scores, namely, in the aspects of student group management and project assessment. This condition shows that these two aspects are the main obstacles that need to be considered in the implementation of project-based learning. In detail, the results of the descriptive analysis of student learning obstacles can be seen in Table 5.

Table 4.
Descriptive Statistical Analysis of Student Sustainability Competencies

Competency Indicators	Mean	Std Deviation	Interpretation of Competency Levels
Systems Thinking Competency (STC)	49.39	19.79	Low
Anticipatory Competency (AC)	50.00	18.99	Low
Normative Competency (NC)	49.27	19.35	Low
Strategic Competency (SC)	49.70	20.64	Low
Collaboration Competency (CC)	51.15	2.85	Low
Self-Awareness Competency (SAC)	51.52	19.05	Low
Problem-Solving Competency (PSC)	48.79	19.39	Low
Mean	**49.97**	**19.72**	**Low**

Table 5.
Results of Descriptive Analysis of Learning Obstacles Among Students When Using the Constructivist Learning Method

Constraint Indicators	Mean	Std Deviation	Category
Managing Time	2.554	0.731	Low
Starting the Course	2.163	0.371	Low
Managing time	2.587	0.495	Low
Managing a group of students	2.021	0.146	Low
Collaborating with others	2.445	0.499	Low
Utilizing learning resources	2.358	0.482	Low
Assessing and evaluating student projects	2.163	0.426	Low
Mean	**2.326**	**0.45**	**Low**

*(The indicators adopted: Liu, 2017, Frensley et al., 2022, Sulisetijono et al., 2024, Occhioni et al., 2024)

The researchers also interviewed lecturers about the obstacles in applying project-based learning. Time management emerged as the most prominent challenge. All lecturers stated that project-based learning activities required a significant amount of additional time, including the planning stage, data collection, guidance process, periodic consultations, and project evaluation. Meanwhile, limited lecture time was often an obstacle to the optimal implementation of all these stages.

(2) Design

The PjBEE learning model consists of the following stages: 1) inquiring, 2) collaborating, 3) decision making, 4) digital action planning, 5) creating artifacts, and 6) action (Figure 1). Descriptions of activities for each stage in the PjBEE model were also designed (Table 6).

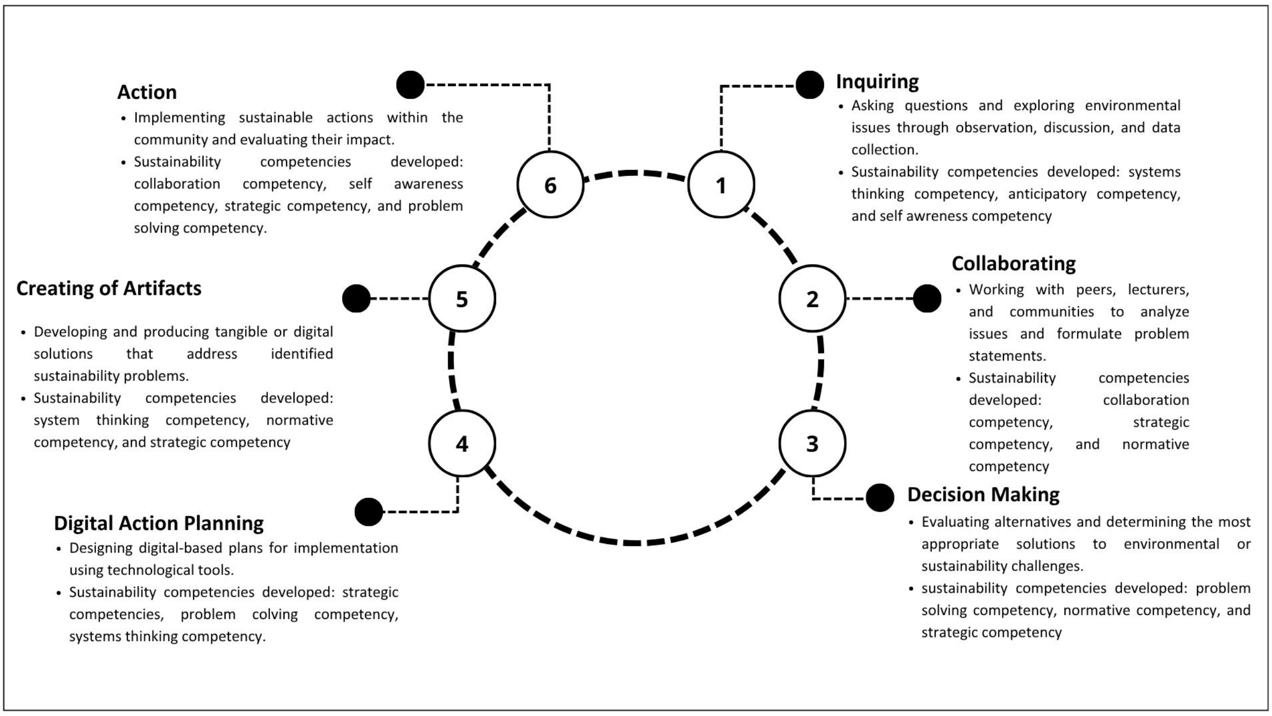

Figure 1. Stages of PjBEE Learning Model

Table 6.
Stages of PjBEE Learning Model

Stage	Lecturer Activities	Students Activities	SCID
Inquiring	Facilitating initial discussions, providing stimuli in the form of environmental issues, guiding students to identify problems.	Ask critical questions, gather preliminary information related to environmental issues through observation and simple literature.	a. Systems Thinking Competence b. Anticipatory Competence c. Self Awareness competence
Collaborating	Guiding students in interacting with relevant communities or societies, providing literature resources, and facilitating group work.	Collaborate with the community, formulate research questions, develop preliminary explanations, and examine information from articles, the internet, and books.	a. Collaboration Competence b. Strategic Competence c. Normative Competence
Decision making	Providing an analytical framework, guiding discussions on evaluating alternative solutions, and directing the selection of the best solution.	Analyzing data/information, evaluating various solution options, and determining the most appropriate and relevant alternative solutions.	a. Problem Solving competence b. Normative Competence c. Strategic Competence
Digital Action Planning	Introducing and guiding the use of technology (software, digital platforms, social media) for action planning.	Developing digital-based action plans by utilizing technology (e.g., digital posters, applications, or collaboration platforms).	a. Strategic Competence b. Systems Thinking Competence c. Problem Solving competence
Creating of Artifacts	Providing technical guidance, giving feedback on product	Design and produce products/artifacts as representations of	a. Systems Thinking Competence

Stage	Lecturer Activities	Students Activities	SCID
	designs, and ensuring alignment with learning objectives.	solutions (e.g., campaign videos, educational modules, or simple prototypes).	b. Normative Competence c. Strategic Competence
Action	Facilitating the implementation of concrete actions in the community, monitoring the implementation of activities, and evaluating the impact of learning.	Carrying out concrete actions for the community, demonstrating solutions, and reflecting on the impact of the activities carried out.	a. Collaboration Competence b. Self Awareness competence c. Strategic Competence d. Problem Solving competence

Note: SCID: Sustainability Competencies Indicators Developed; *Source: (Stapp, 1974; Krajcik & Blumenfeld, 2006).

(3) Develop

The development stage produced a prototype of the PjBEE model that was validated by experts in biology education and environment-based learning. Validation was carried out on the aspects of Objectives, Supporting Theory, Learning Syntax, Social System, Reaction Principles, Support System, and Instructional Impact and accompanying impact. Objectives, these are the specific goals that the instructional model aims to achieve. They guide the design process and ensure that the learning outcomes are measurable and aligned with the learners' needs (Wongpairin & Songsern, 2022). Supporting Theory, this involves the theoretical framework that underpins the instructional model. It ensures that the model is grounded in established educational theories and principles, providing a solid foundation for its design and implementation (Abdolahi et al., 2021). Learning Syntax, this refers to the sequence and structure of learning activities within the model. It ensures that the instructional process is logically organized and facilitates effective learning (Boa et al., 2018). Social System: This component addresses the social interactions and collaborative aspects of the learning environment. It emphasizes the importance of peer interactions and the role of the instructor in facilitating a supportive learning community (Iyamuremye et al., 2025). Reaction Principles: These are the guidelines for how instructors and learners should respond to various situations within the learning process. They help in managing classroom dynamics and ensuring that the learning environment remains conducive to achieving the instructional objectives (Boa et al., 2018). Support System, this includes the resources and tools that support the instructional process, such as educational technologies, instructional materials, and administrative support. It ensures that both instructors and learners have the necessary resources to succeed (Tran et al., 2025). Instructional Impact, this measures the direct effects of the instructional model on learners' knowledge, skills, and attitudes. It involves assessing whether the instructional objectives are being met and how effectively the model facilitates learning (Moreira Mora & Espinoza, 2016). Accompanying Impact, this refers to the broader, often unintended effects of the instructional model, such as its impact on learners' motivation, engagement, and overall educational experience. It ensures that the model contributes positively to the learners' holistic development (Moreira Mora & Espinoza, 2016).

Based on the validation results by three validators, all indicators obtained an average score above 90% with a category of very valid (Table 7). This shows that the Project-Based Environmental Education (PjBEE) learning model book has clear objectives, adequate theoretical support, systematic learning syntax, a relevant social system, appropriate reaction principles, strong system support, and significant instructional impact. Therefore, the PjBEE model book is deemed suitable for use in learning without major revisions. The inter-rater reliability value of 0.905 (Table 8) indicates that the consensus or agreement among the experts is in a good category.

Table 7.
Results of the PjBEE learning model validation

Indicator	Validator 1	Validator 2	Validator 3	Average Score (%)	Category
Objectives	92	92	91	91.67	Very Valid
Supporting Theory	88	87	89	88.00	Very Valid
Learning Syntax	88	90	88	88.67	Very Valid
Social System	90	92	91	91.00	Very Valid
Reaction Principles	93	90	93	92.00	Very Valid
Support System	93	93	92	92.67	Very Valid
Instructional Impact and Accompanying Impact	95	94	93	94.00	Very Valid
Average	**91.29**	**91.14**	**91.00**	**91.14**	**Very Valid**

Note: Validator 1 (Environmental education and curriculum development), Validator 2 (biology education lecturer and practitioner

Table 8.
Intraclass Correlation Coefficient

	Intraclass Correlation	95% Confidence Interval		F Test True Value 0			
		Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	.760[a]	.377	.949	10.509	6	12	.000
Average Measures	.905[c]	.645	.982	10.509	6	12	.000

(4) Implementation

The implementation phase aims to test the feasibility and acceptability of the Project-Based Environmental Education (PjBEE) learning model before conducting a more extensive field trial. Implementation is carried out in two stages, namely a one-to-one trial and a small group trial. The participants in the one-to-one trial consisted of three pre-service biology teachers in the third semester who had previously completed the Environmental Education course. The One-to-One Trial is an initial trial involving three students selected based on different academic ability levels, namely low, medium, and high. During the learning process, the researchers observed the students' understanding of the instructions, the clarity of the learning steps, and the suitability of the material to the students' ability levels. After the trial, the three students were asked to provide feedback, comments, and suggestions regarding the readability of the teaching materials, the clarity of the instructions, and the relevance of the learning activities (Table 9). This task was followed by a small group trial. The subjects at this stage were nine students divided into three groups. Each group consisted of three students with varying levels of ability, namely low, medium, and high ability groups. During the implementation, the researcher observed the interactions between students in completing project-based tasks according to the PjBEE model flow. The focus of the observation was on activity, ability to work together, and the effectiveness of learning instructions. After the activity, all students provided feedback in the form of comments and suggestions (Table 9).

Table 9.
Results from One-To-One Trials and Small Group Trials on the PjBEE Learning Model

Trial Phase	Things to Improve	Repair
One-to-One Trial	The individual trial indicated that the PjBEE model was generally comprehensible but required refinement in terms of clarity, contextualization, and task differentiation to accommodate students' heterogeneous abilities.	a. Simplify and restructure instructional steps using concise and accessible language. b. Incorporate more contextualized and locally relevant case examples. c. Provide differentiated project options with varying levels of complexity.
Small Group Trial	The small group trial highlighted the necessity of enhanced visual and structural support, improved time management, and strategies for equitable participation to maximize the	a. Integrate visual scaffolding tools (e.g., flow diagrams, infographics). b. Adjust the allocation of time to ensure balance between discussion, project execution, and reflection.

Trial Phase	Things to Improve	Repair
	collaborative and cognitive benefits of the PjBEE model.	c. Introduce tiered project challenges to stimulate higher-order thinking. d. Establish clear role distribution to foster equitable collaborative engagement.

(5) Evaluation

The Project-Based Environmental Education (PjBEE) model was implemented in the field test phase to measure the feasibility and effectiveness of learning. The field test involved third-semester pre-service biology teachers enrolled in the Environmental Education course. This stage was conducted after the small-group trial, aiming to examine how the model functioned in broader instructional contexts and to confirm its applicability in the higher education curriculum. The assessment mechanism was carried out through a combination of classroom observations, student response questionnaires, and sustainability competency tests. The field test was conducted by researchers to assess the implementation of the model syntax in real learning conditions. The results of the observation indicated that lecturers and students carried out all stages of PjBEE well according to the design. The feasibility of the model was demonstrated by the implementation of lecturer and student activities (Table 10) and reinforced by student responses that gave positive responses to the implementation of PjBEE (Table 11). Therefore, the PjBEE model has demonstrated its practicality and effectiveness, paving the way for its wider application in environmental-based learning.

Table 10.
Results of Observation of PjBEE Model Implementation

Learning stages	Lecturer observation (%)	Criteria	Student observation (%)	Criteria
Inquiring	98.00	Very Practical	97.50	Very Practical
Collaborating	99.00	Very Practical	96.80	Very Practical
Decision Making	97.00	Very Practical	95.20	Very Practical
Digital Action Planning	96.00	Very Practical	94.70	Very Practical
Creating Artifacts	100.00	Very Practical	96.50	Very Practical
Action	99.00	Very Practical	95.80	Very Practical
Average	**99.50**	**Very Practical**	**96.10**	**Very Practical**

The implementation of the PjBEE learning model is considered very practical, with an average lecturer activity score of 99.5% and an average student activity score of 96.1%. This achievement indicates that each stage of PjBEE, from inquiring to action, can be implemented as designed. This reinforces that the PjBEE model has a high level of practicality in supporting project-based learning processes.

Table 11.
Student Responses to the Implementation of the PjBEE Model

No.	Assessment Aspects	Mark	Criteria
1.	With the PjBEE model, I have a strong willingness to engage in the learning process.	89.2	Positive
2.	The PjBEE model is interesting and not monotonous.	88.5	Positive
3.	The PjBEE model helps me to easily understand the concepts.	87.9	Positive
4.	With the PjBEE model, I can solve problems in the learning process more effectively.	86.7	Positive
5.	The PjBEE model facilitates my learning process and helps me to search for information from valid sources.	88.3	Positive
6.	The PjBEE model motivates me to collaborate with communities or society.	89.6	Positive
7.	The PjBEE model encourages me to be more active in the learning process.	87.4	Positive
8.	The PjBEE model motivates me to contribute to environmental sustainability.	90.1	Positive
9.	The PjBEE model provides activities related to environmental sustainability (critical thinking, problem-solving, sustainable competencies) needed in the 21st century.	89.7	Positive

No.	Assessment Aspects	Mark	Criteria
10.	Inquiring: I am able to formulate questions related to environmental issues faced by local communities.	86.8	Positive
11.	Collaborating: I can work collaboratively with peers and communities in analyzing problems and formulating solutions.	87.6	Positive
12.	Decision Making: I can evaluate alternative solutions and select the most appropriate one based on available data.	88.0	Positive
13.	Digital Action Planning: I am able to use digital tools to design plans for solving environmental problems.	86.9	Positive
14.	Creating Artifacts: I can design and produce products that reflect the solutions to the identified problems.	87.2	Positive
15.	Action: I am able to implement real actions in the community to contribute to solving environmental problems.	89.0	Positive
16.	The PjBEE model should be applied to other courses related to environmental education.	90.3	Positive
17.	Average	88.4	Positive

The mean reaction of students to the adoption of the PjBEE model was 88.4% favorable. This verifies that students reacted positively and with enthusiasm to the implementation of PjBEE in the Environmental Education course. The findings indicate that PjBEE may generate learning experiences tailored to students' requirements. Consequently, more effective testing is essential to assess the impact of PjBEE on enhancing students' sustainability competencies. At this stage, researchers performed an analysis to evaluate the efficacy of the PjBEE learning model in enhancing students' sustainability abilities. The efficacy criteria were established via inferential analysis by contrasting students' pre-test and post-test scores (Table 12). Before executing the impact test, fundamental assumptions regarding data normality and homogeneity were examined in both the pre-test and post-test outcomes of sustainability skills. This study sought to confirm that the research data satisfied the criteria for subsequent inferential testing.

Table 12.
Results of the Prerequisite Sustainability Competency Test for Students

Variable	Value (Sig.)	Category
Normality in the pretest	.227	Normal
Normality in the posttest	.796	Normal
Homogeneity	.283	Homogeneous

The results of the paired sample t-test show a significance value (Sig. 2-tailed) of 0.000 < 0.05. Thus, there is a significant difference between the pretest and posttest sustainability competencies of students. This indicates that the application of the PjBEE learning model has a positive effect on improving student competencies. The average score of students' sustainability competencies post-implementation of the PjBEE learning model exceeded the average score before its application (Figure 2).

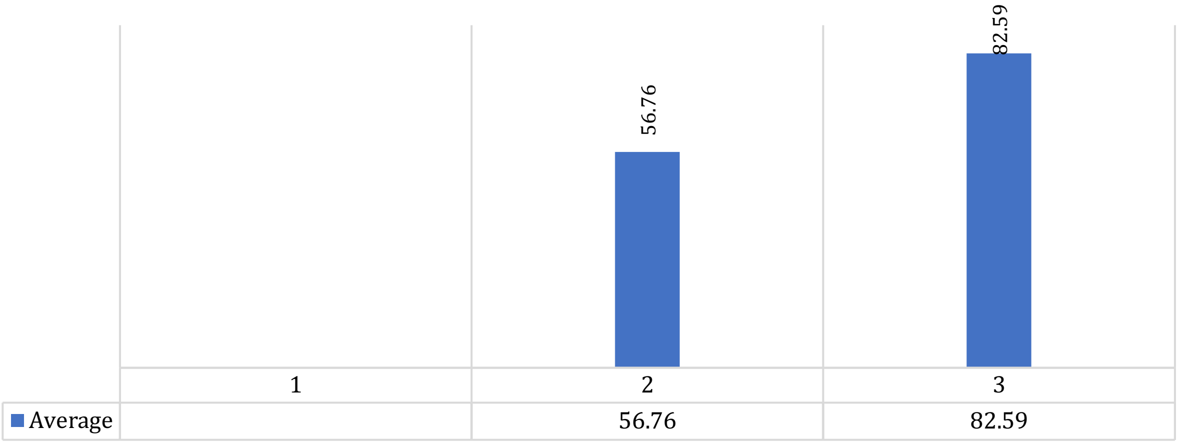

Figure 2. Effectiveness of the PjBEE Learning Model

The results of the analysis show that the average sustainability competencies of students are in the low category. This condition confirms the existence of a clear disparity among students, resulting in uneven competency achievement. The development of sustainability competencies through project-based learning (PBL) is often uneven, with some students showing significant improvement while others experience only minor changes. This variability highlights the need for more adaptive learning models to reduce competency gaps among students. Research indicates that while PBL can effectively foster key competencies in sustainability, the outcomes can be inconsistent due to various factors such as the balance between student autonomy and instructor support, and the real-world applicability of projects (Bramwell-Lalor et al., 2020; Terrón-López et al., 2020; Birdman et al., 2022). For instance, a study found that the defining aspects of PBL, including collaboration and real-world connection, contribute to students' self-perceived competence development, but the effectiveness depends on how well the pedagogical challenges are managed (Birdman et al., 2022). Another study emphasized that adaptive learning models, which personalize learning experiences based on individual needs, can enhance student engagement and learning outcomes, thereby addressing the uneven development of competencies (Aymane et al., 2024; Alvarez-Icaza et al., 2024; Sari et al., 2025). Therefore, designing more adaptive and inclusive learning models is crucial to ensure that all students can develop the necessary sustainability competencies effectively.

The primary challenges identified included the management of student groups and the assessment of projects. The obstacles directly affect the effectiveness of project-based learning. Insufficiently structured group collaboration and incomplete project evaluations significantly hinder the development of sustainability competencies. Empirical evidence suggests that structured teamwork and comprehensive project assessments are crucial for fostering essential skills such as communication, teamwork, and stakeholder engagement, which are vital for sustainability education (Konrad et al., 2020; Rahat et al., 2022; Aljaaidi et al., 2025). In this study, interviews with lecturers also highlighted time constraints as a dominant challenge. In this study, interviews with lecturers also highlighted time constraints as a dominant challenge. Structural factors such as the duration of the project and institutional support significantly influence the success of project-based learning (PBL) implementation. Institutional support, including resources and commitment from various levels within the educational institution, plays a crucial role in motivating teachers and ensuring the persistence of PBL initiatives (Walsh et al., 2008; Walsh, 2009; Lam et al., 2010). Additionally, the involvement of external partners, such as industry, can enhance the effectiveness and sustainability of PBL programs by providing practical insights and financial support (Walsh et al., 2008; Walsh, 2009). The duration of the project also impacts the success of PBL, as longer-term projects allow for deeper engagement and more meaningful learning experiences (Liu et al., 2025). The PjBEE model is developed to address variations in students' initial competencies, enhance group management, and establish a more transparent project assessment system. Conversely, institutional support through flexible time allocation is essential for successful implementation.

The PjBEE learning model is designed through six stages: inquiring, collaborating, decision making, digital action planning, creating artifacts, and action. The philosophical basis of the inquiring stage is constructivist theory, which emphasizes that knowledge is not passively transferred from lecturers to students, but is actively constructed through the process of questioning, observing, and connecting new experiences with prior knowledge. Constructivism posits that learning is an active process where learners construct new knowledge based on their previous experiences and interactions with their environment (Schreurs & Al-Huneidi, 2011; Tafrova-Grigorova, 2016; Pang et al., 2020). This theory highlights the importance of active engagement, where students are encouraged to question and challenge content, thereby constructing their own understanding (Ford, 2010; Caceffo & Azevedo, 2014). The constructivist approach involves learners actively participating in their learning process through hands-on activities, discovery, and inquiry, which helps them to transform information and build new knowledge (Kumari, 2009; Tafrova-Grigorova, 2016). In the inquiring stage, students learn to build initial knowledge about sustainability issues through activities that explore relevant problems in their surroundings. This process reflects the principle of constructivism, which emphasizes that learning is an active and meaningful activity, where knowledge is constructed by students themselves through experience and critical reflection.

Vygotsky's sociocultural theory offers significant insights into the processes of collaboration and decision-making. This theory posits that learning occurs within a social context and is profoundly influenced by interactions among individuals, cultures, and languages (Saljo, 2011; Ahmad Zainuddin et al., 2012; Lambright, 2024). Through collaboration, students learn in groups, exchange ideas, and utilize the zone of proximal development (ZPD) to improve their understanding through guidance from peers and lecturers. Collaborative learning activities, such as those facilitated by virtual entities or immersive learning environments, extend the ZPD by simulating interactions with competent peers (Tarouco et al., 2018). The ZPD, defined as the distance between what a learner can do independently and what they can achieve with guidance, is crucial in this process (Lerch et al., 2005). By working within their ZPD, students move from needing constant assistance to becoming knowledgeable participants, often providing scaffolding for their peers. This collaborative approach not only enhances critical thinking skills but also fosters a deeper understanding of the subject matter through shared problem-solving and discourse activities (Kaup & Dau, 2024; Khusna et al., 2025). Additionally, the integration of digital artifacts and structured discussion forums further supports the ZPD by enabling students to reflect on and transform their learning practices collectively (Ojha et al., 2022; Kaup & Dau, 2024).

At the decision-making stage, social cooperation becomes the basis for students in constructing arguments, selecting alternative solutions, and determining strategic steps. This process reflects the role of social interaction in cognitive development as emphasized by sociocultural theory. Social-cognitive conflict, which arises from peer interactions and differing viewpoints, enhances cognitive growth by promoting intellectual progress through cooperation and verbal expression (Gavilan Bouzas, 2009; Roselli et al., 2022). Sociocultural theories highlight that learning is stimulated and nourished by interactions with others, supporting the view that learning is essentially a socially inspired process (Matthews & Cobb, 2005). Cooperative learning models, grounded in Piaget's genetic-epistemological theory and Vygotsky's sociocultural theory, demonstrate that grouping students in small homogenous or heterogeneous groups fosters the adoption of both declarative and procedural knowledge (Miščević-Kadijević, 2009). Additionally, social learning in cooperative decision-making varies across cultural contexts, indicating that societal background impacts how individuals learn and cooperate (Molleman & Gaechter, 2018).

The stages of digital action planning are closely related to transformative learning theory. Transformative learning occurs when individuals critically reflect on their experiences, leading to changes in their thinking and actions (Gravett, 2004; Hodge, 2014). This process involves gaining awareness of current habits of mind, critiquing assumptions, assessing alternative views, and deciding to adopt new perspectives or synthesize old and new ones to guide future actions 1. Transformative learning is not just about solving problems but involves a continuous process of questioning and adapting to emerging complexities (Yeo & Gold, 2011). This reflective and adaptive approach is essential in digital action planning, where integrating new technologies and methodologies requires ongoing critical reflection and transformation (Moreira, 2024; Schwinn et al., 2024). The stages of creating artifacts are closely related to transformative learning theory. Mezirow emphasizes that transformative learning occurs when individuals critically reflect on their experiences, then change their thinking and actions. Transformative learning theory focuses on the process of changing one's perspective through critical reflection and self-questioning, which leads to a transformation in worldview and behavior (Hodge, 2011; Hill et al., 2020; Brendel, 2022). This theory is particularly relevant in contexts where learners engage in creating artifacts, as the process often involves deep reflection and the re-evaluation of previously held assumptions (Hodge, 2014; Singer-Brodowski, 2023). By critically analyzing their experiences and the artifacts they create, individuals can undergo significant cognitive and emotional changes, aligning with Mezirow's concept of transformative learning (Hodge, 2011; Hill et al., 2020; Hodge, 2014).

The stages of action are closely related to transformative learning theory. Mezirow emphasizes that transformative learning occurs when individuals critically reflect on their experiences, then change their thinking and actions. Transformative learning involves a profound change in both thinking and behavior, often triggered by a "disorienting dilemma" that prompts critical reflection, leading to a shift in perspective and subsequent change in actions (Jones, 2020). This process is characterized by phases such as acquiring knowledge, taking actions, and generating wisdom, which collectively fulfill the transformative learning cycle (Chang, 2021). Additionally, transformative learning is not only about rational and reflective actions but also involves spontaneous actions that introduce novelty and are later reflected upon by the individual (Nohl, 2009). This comprehensive approach underscores the importance of critical reflection and subsequent action in achieving transformative learning outcomes

(Keegan, 2011). The PjBEE learning model integrates constructivism, sociocultural, and transformative theories to support the comprehensive development of students' sustainability competencies.

The Develop stage indicates that the PjBEE learning model prototype has received validation from specialists in biology education and environment-based learning. The evaluated components encompassed Objectives, Supporting Theory, Learning Syntax, Social System, Reaction Principles, Support System, and Instructional Impact, along with their associated effects. All indicators attained an average score within the very valid category, and the inter-rater reliability score demonstrated strong unanimity among the validators. The findings indicate that the PjBEE model has achieved elevated instructional validity requirements and adequate expert consensus for implementation in learning without significant modifications. Validating learning models is an essential phase in developmental research to ascertain their validity, practicality, and efficacy, so ensuring they address educational requirements and enhance learning outcomes (Vandewaetere et al., 2011; Astutik et al., 2020; Fatimah, 2020; Siagian et al., 2023; Sunardianta et al., 2024; Amin et al., 2025).

High validity and reliability are crucial for the credibility of research findings. Instruments with high reliability produce consistent results, reducing random error, while high validity ensures that the instrument accurately measures the intended concept, minimizing systematic error (Ouzouni & Nakakis, 2011; Ahmed & Ishtiaq, 2021). With high validity and good inter-rater reliability, PjBEE is considered suitable for use in learning. This suggests that subsequent phases in model development, such as field testing and efficacy assessments, can proceed without requiring substantial changes to the model's core structure (Schneider et al., 2016; Barbosa et al., 2016). Moreover, attaining expert consensus can enhance the trust of educators and institutions in the model, hence promoting its integration into the curriculum. Nonetheless, despite the exceptional validity and reliability, additional research should focus on whether the application of this model preserves these attributes in actual classroom settings, assessing the tangible effects on student competence, scalability, and contextual variables such as resources and lecturer/student conditions.

The Implementation phase of the PjBEE learning model development seeks to evaluate the model's practicality and acceptability prior to extensive field testing. In the implementation phase of the ADDIE model, the developed instructional designs are trialed in real educational settings to evaluate their feasibility and acceptability, with an emphasis on gathering empirical user feedback, preparing both instructors and learners, and ensuring organizational readiness before embarking on extensive field testing (Pearson et al., 2020; Paidi et al., 2024). The implementation involved two stages of testing: one-to-one trials and small-group trials. The first stage, one-to-one trials, focused on evaluating the instructional sequence with individual students to assess its effectiveness and gather detailed feedback. The second stage, small-group trials, involved testing the instructional sequence with a small group of students to observe its impact in a more collaborative learning environment and to refine the instructional design based on group dynamics and interactions (Felderer & Auer, 2016; Çelik & Güzel, 2019; Andika et al., 2019).

In a one-to-one trial, three students with different ability levels (low, medium, and high) were selected to test aspects such as understanding of instructions, clarity of learning steps, and the suitability of the material to student abilities. Feedback from students indicated that the model was generally understandable, but still required improvement in terms of clarity, contextualization, and task differentiation to accommodate the heterogeneity of student abilities. Students indicated that the model was generally understandable, but still needed improvement in terms of clarity, contextualization, and task differentiation to accommodate the heterogeneity of student abilities. Research highlights that instructional clarity is crucial for enhancing students' motivation and task value (Kelly et al., 2024; Oschwald et al., 2025; Zhang et al., 2025). Effective instructional differentiation, which involves adapting teaching strategies to diverse learner characteristics, is essential for addressing the varied educational needs of students (Jang et al., 2018; Tomlinson, 2021; Jager et al., 2025). Additionally, contextualized tasks and meaningful work are central to effective instruction, helping students connect theoretical concepts to practical applications (Butler, 2003; Clarke & Roche, 2018).

The small-group trial phase had nine students categorized into three diverse groups based on ability: low, medium, and high. Observations concentrated on collaborative activities among students, instructional efficacy, and interactions during project task completion in accordance with the PjBEE paradigm. This phase underscored the critical need to upgrade visual aids (Shapiro, 1994; Saidhujaeva, 2023) and organizational frameworks (Weber et al., 1997; Deokar et al., 2004; Cui, 2025), improve time management practices (Hameri & Heikkilä, 2002; Ballard & Seibold, 2003; Wang et al., 2010), and implement strategies that guarantee balanced and equitable involvement (Reinig & Mejias, ; Gutiérrez-Ortega et al., 2020; Rodney et al., 2024) for every team member.

The implementation phase indicates that while the PjBEE model has considerable appeal, many practical elements require enhancement to optimize its application in an academic setting. These improvements include simplifying instructions using language that is easier to understand, contextualizing material to students' local conditions, differentiating tasks, and designing more realistic visual scaffolding and time management. Research indicates that making instructional materials more accessible and easier to comprehend can significantly enhance student engagement and learning outcomes (Neris et al., 2005; Almekhlafi et al., 2020). Contextualized instructional materials, which integrate local and relevant examples, have been shown to improve student motivation and engagement, although the impact on academic performance may vary (Ondrada et al., 2024; Rocha-Feregrino & Sánchez, 2025). Differentiated instruction, which tailor tasks to meet the diverse needs and abilities of students, is recognized as an effective strategy to support varied learning styles and improve overall educational outcomes (Lam et al., ; Schwerin et al., 2021). The use of visual aids and structured time management strategies can enhance the usability and effectiveness of instructional materials, making them more engaging and easier for students to navigate (Neris et al., 2005; Irasuti & Bachtiar, 2024; Wang et al., 2023).

The evaluation findings indicate that the PjBEE learning model has a high degree of practicality and efficacy. Observations of lecturer and student activities indicate that the entire learning process, from inquiry to action, was effectively executed according to the design. This conclusion is supported by various studies that highlight the importance of aligning learning design with classroom observations to enhance teaching and learning practices. For instance, systematic literature reviews have shown that integrating learning design with multimodal observations can significantly improve the effectiveness of teaching strategies (Eradze et al., 2019). Additionally, research on student learning outcomes and classroom observations reveals that these methods are crucial for evaluating teacher effectiveness and ensuring that educational objectives are met (Fan, 2023). Furthermore, studies on effective learning designs emphasize the feasibility of transferring successful teaching practices across different contexts, thereby promoting quality education (Cameron, 2009). Observations of lecturers' teaching behaviors and students' engagement further validate the effectiveness of well-designed learning activities (Nambiar et al., 2011; João & Silva, 2025). Overall, the evidence suggests that when learning designs are meticulously planned and executed, they lead to productive and engaging educational experiences for both lecturers and students (Maulana & Helms-Lorenz, 2016; van der Lans, 2018).

Student feedback about the implementation of PjBEE indicates a favorable trend. Students perceive PjBEE as engaging, not tedious, beneficial for comprehending topics, fostering teamwork, and enhancing motivation to support environmental sustainability. Sustainability-based learning models, have been shown to significantly enhance students' active participation in addressing real-world community problems. These models engage students in practical, hands-on experiences that bridge the gap between theoretical knowledge and real-world application, fostering essential problem-solving and analytical skills (Steinemann, 2003; Christiansen et al., 2017; Kricsfalusy et al., 2018; Ruthanam, 2025). Students develop critical cognitive and professional skills by tackling complex, interdisciplinary, and real-world problems (Steinemann, 2003; Cong & Ironsi, 2025). These models often involve collaborations with local businesses, non-profits, and community organizations, providing students with real-life experiences and opportunities to contribute to community sustainability efforts (Rowe & Hiser, 2015; Christiansen et al., 2017). Courses designed around sustainability-based learning often incorporate interdisciplinary training, service learning, and professional practice, which enrich students' educational experiences and prepare them for diverse professional environments (Kricsfalusy et al., 2018; Sohaee & Farsad, 2025). Community-based and service-learning programs have been found to significantly influence students' participation in sustainable development initiatives, promoting a deeper understanding of sustainability issues and encouraging proactive involvement (Ruthanam, 2025; Kumar et al., 2024). Student feedback about the implementation of PjBEE indicates a favorable trend. Students perceive PjBEE as engaging, not tedious, beneficial for comprehending topics, fostering teamwork, and enhancing motivation to support environmental sustainability. The average sustainability competency score of students after the implementation of PjBEE was higher than before its implementation, indicating that this model is effective in improving sustainability competencies (Kricsfalusy et al., 2018; Ismail et al., 2025).

CONCLUSION

The results of expert validation indicated that the PjBEE model meets the criteria of a highly valid educational product, particularly in terms of content relevance, syntactic structure, and implementation feasibility. The findings from classroom implementation further revealed that the model is both practical and effective in facilitating meaningful learning experiences that strengthen students' sustainability competencies. Specifically, the application of the PjBEE model was found to improve several core competencies, including systems thinking, anticipatory, normative, strategic, collaboration, self-awareness, and problem-solving competencies that are essential for future biology educators in addressing sustainability-related issues. Students' positive responses, together with the significant improvement in post-test results, demonstrate that the PjBEE model effectively integrates sustainability principles into the learning process. Therefore, the PjBEE model can be considered a pedagogically sound and empirically supported framework for fostering sustainability-oriented education within teacher preparation programs, particularly in the field of biology education.

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