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BioDiv-Web: Integrating structured project-based learning with citizen science to enhance critical thinking and environmental literacy

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ABSTRACT

The escalating global biodiversity crisis underscores the critical need for effective educational strategies that promote environmental awareness and competencies. This research and development study addresses this imperative by designing and evaluating "BioDiv Web," an innovative e-learning platform for biodiversity education. The platform synergistically integrates the Structured Project-Based Learning (SPjBL) model with a Citizen Science Project (CSP) approach to create an authentic and scaffolded learning environment. Developed using the Lee and Owens model, the product was validated by experts and deemed highly valid (e.g., material validation: 100%) and practical (average score: 92%) based on trials with students. A quasi-experimental study involving 70 tenth-grade students was conducted to assess its effectiveness. The experimental group exhibited significantly higher learning gains compared to the control group. The results demonstrated moderate effectiveness, with normalized gain scores of 0.68 for critical thinking skills and 0.65 for environmental literacy. One-way ANCOVA analysis confirmed that these improvements were statistically significant ($p < 0.001$). The findings affirm that the BioDiv Web platform is a robust, practical, and effective digital tool for enhancing senior high school students' critical cognitive and affective learning outcomes in biodiversity education.

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INTRODUCTION

The global crisis of biodiversity loss poses a significant threat to ecosystem services, exacerbated by anthropogenic activities such as deforestation, pollution, and land conversion (Marselle, 2019; Hughes et al., 2022; Rahardyan & Nugraheni, 2024). This issue underscores the urgent need for educational interventions to foster conservation awareness, particularly through integrating biodiversity content into school curricula (Aufa & Nursiwi, 2024; Indahri, 2020; Ardoin et al., 2020). Environmental education aims to transform behaviors by enhancing knowledge, skills, and awareness of environmental issues, enabling students to analyze problems like species extinction and habitat degradation using critical thinking (Chawla, 2021; Saleh, 2018).

Critical thinking skills are essential 21st-century competencies that enable students to analyze data, evaluate arguments, and formulate evidence-based conclusions (Greenstein, 2012). However, preliminary study results from SMA N I Kragan students revealed an average score of 59, categorized as needing guidance, with details showing 36% of 61 students needing guidance, 38% sufficient, 15% good, and 12% very good, indicating low critical thinking proficiency. Meanwhile, teachers acknowledge the importance of integrating critical thinking but face challenges due to limited instructional media and contextual learning resources.

Despite these efforts, gaps exist in current research where educational approaches often lack empirical integration of critical thinking with environmental literacy, resulting in suboptimal student outcomes (Ardoin et al., 2020; Chawla, 2021; Sarıgöz, 2023). For instance, studies show that while biodiversity education improves basic knowledge, it fails to significantly enhance critical thinking skills, with quantitative data indicating only marginal gains compared to holistic literacy programs (Saleh, 2018). Theoretical frameworks, such as those from Piaget's cognitive development theory emphasizing active problem-solving, highlight the need for experiential learning to bridge this gap, yet many interventions remain theory-heavy without practical application (Juliyanti & Syahfitri, 2024; Ardoin et al., 2020).

Environmental literacy also plays a crucial role in biodiversity education, encompassing ecological knowledge, cognitive skills, affective attitudes, and pro-environmental behavior (Hermawan et al., 2022; Roland W Scholz, 2011). Environmental literacy assessment yielded an average score of 271, categorized as moderate, based on a 30-item multiple-choice test and a 40-statement questionnaire, highlighting deficiencies in cognitive skills and environmental attitudes (Kollmuss & Agyeman, 2010; Monroe et al., 2019). Hence, an innovative intervention that integrates environmental literacy explicitly through contextual and project-based learning is required.

While context-based learning, utilizing environmental surroundings as resources, can bolster conceptual understanding (Sukardiyono & Rosana, 2019), biodiversity education in schools remains predominantly theoretical, failing to encourage active student engagement (Ardoin et al., 2020). Consequently, innovative approaches like citizen science are essential, with Citizen Science Projects (CSP) proving effective in engaging learners in authentic scientific inquiries through public-scientist collaborations (Bonney, McCallie, et al., 2009; MacPhail & Colla, 2020).

Empirical studies have demonstrated that CSP participation improves students' environmental awareness, critical thinking, and scientific understanding (Ballard et al., 2017; Lewandowski & Oberhauser, 2016; Shirk et al., 2012). Integrating technology can further enhance CSP-based learning. Learning Management Systems (LMS) such as Moodle or WordPress support collaboration, feedback, and project documentation (Newman et al., 2012; Sullivan et al., 2009). When connected with platforms like iNaturalist, LMS-based citizen science projects can effectively foster biodiversity observation, data analysis, and reflective learning (Ballard et al., 2017; Lewandowski & Oberhauser, 2016). However, unstructured project implementation may limit learning outcomes, highlighting the need for guided frameworks (Phillips et al., 2018). So that, the Structured Project-Based Learning (SPjBL) model were required.

SPjBL provides a systematic sequence that ensures conceptual depth and meaningful learning (Muntholib et al., 2024). When combined with CSP, SPjBL helps students connect theoretical knowledge with real-world biodiversity issues while promoting metacognitive awareness and research skills. Empirical studies confirm that structured digital learning environments enhance learning outcomes more effectively than conventional instruction (Koç & Kanadlı, 2025a).

To address these gaps, this study proposes a novel integration of Structured Project-Based Learning (SPjBL) with Citizen Science Projects (CSP) in a web-based platform called BioDiv-Web which designed to enhance critical thinking and environmental literacy through authentic, collaborative activities (MacPhail & Colla, 2020; Bonney et al., 2009; Ballard et al., 2017). This approach leverages CSP's experiential learning to involve students in real scientific processes, such as data collection on biodiversity, while SPjBL provides structured phases for guided inquiry and reflection, ensuring deeper conceptual understanding (Shirk et al., 2012; Lewandowski & Oberhauser, 2016; Echeverria et al., 2021). This research aims to develop and evaluate the BioDiv-Web platform, integrating SPjBL and CSP, to improve students' critical thinking skills and environmental literacy in biodiversity education.

RESEARCH METHODS

Research Design

This study employs a research and development (R&D) design aimed at producing an LMS-based website for the topic of Biodiversity. The research and development model used refers to the framework proposed by Lee & Owens (2004). The Lee and Owens model was selected because it represents a multimedia-based instructional design model. The following diagram illustrates the modified version of the Lee and Owens development model. A detailed description of the modified Lee and Owens model as applied in this study is presented in Figure I.

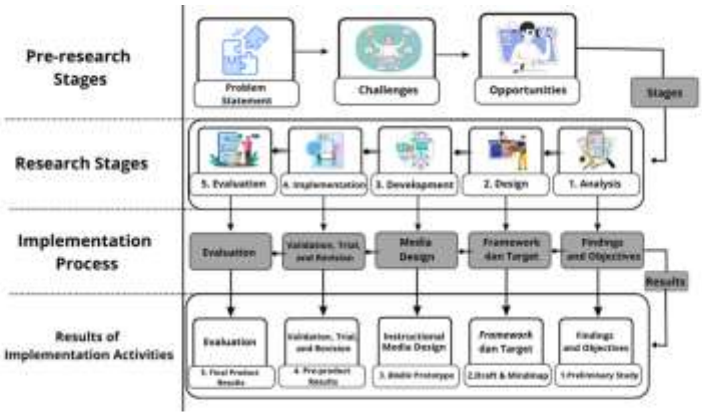

Figure I. Research design modified from Lee and Owen stages (modified by researcher, 2025)

Population and Samples

The population of this study consisted of all 355 tenth-grade students enrolled at SMAN I Kragan, Rembang, Central Java. From this population, a total of 70 students from classes X-2 and X-7 were selected as the research sample. The sampling procedure employed a simple random sampling technique, in which participants were randomly chosen from the population without consideration of any existing strata (Sugiyono, 2017). This technique was chosen because it ensures each member of the population has an equal chance of being selected, minimizing sampling bias and allowing for generalization of results to the broader population, which is essential for quantitative studies in educational settings (Creswell & Creswell, 2018; Fraenkel et al., 2019). Validation of the developed product involved four experts: a media expert, a content expert, a learning instrument expert, and an educational practitioner. These validators assessed the product in terms of its content accuracy, instructional design, and practical applicability in the classroom setting.

Instruments

The research instruments used in this study were designed to measure students' critical thinking skills and environmental literacy. All instruments were developed and validated to ensure their reliability, validity, and appropriateness for use with senior high school students.

Critical Thinking Skills Instrument

The instrument for measuring students' critical thinking skills was adapted from the indicators and descriptors proposed by Greenstein (2012). This instrument consists of multiple-choice questions assessing various dimensions of critical thinking, including apply, evaluate, use data to develop critical insight, analyze, and synthesize. To ensure the instrument's quality, item analysis was conducted on the test results from 61 students. The validity of each item was determined using Pearson's Product-Moment correlation. Critical r-table value of 0.254 for a significance level of 5% used, 12 out of the 13 items were declared valid. One item was identified as invalid and was therefore not used in the final analysis.

The reliability of the test was calculated using Cronbach's Alpha formula. The result was $\alpha = 0.642$. This value exceeds the standard reliability threshold of 0.6, indicating that the instrument is reliable and internally consistent for measuring critical thinking skills (Arikunto, 2018). The difficulty Index showed that all items had a difficulty index (P) ranging between 0.41 and 0.74. This places all questions in the "moderate" category (0.31 – 0.70), confirming that the test was neither too easy nor too difficult for the student cohort. The discriminating power (D) of the items varied, with most items falling into the "Good" category ($D > 0.40$), and two items even achieving the "Excellent" category ($D > 0.70$). This indicates that the test was effective in differentiating between high-achieving and low-achieving students. The rigorous analysis confirms that this multiple-choice test, grounded in Greenstein's framework, is a valid and reliable tool for assessing critical thinking skills in an educational context.

Environmental Literacy

The research instrument used in this study is an environmental literacy instrument adapted from the Middle School Environmental Literacy Survey/Instrument (MSELS, 2012). This instrument comprises two main types: a multiple-choice test and a questionnaire on student environmental literacy. The test consists of 30 multiple-choice items, while the questionnaire includes 31 statement items, totaling 61 items. These items measure key indicators of environmental literacy, including ecological knowledge (items 1-20), cognitive skills (items 21-30), attitudes toward the environment (items 31-40), and environmental behavior (items 41-61), as outlined in the adapted indicators.

To ensure suitability for research, the instrument underwent validity and reliability testing. Validity analysis showed that all 61 items have Pearson correlation values (R count) ranging from 0.182 to 0.700, all exceeding the critical value (R Table = 0.058 at 5% significance), indicating high validity. Reliability testing yielded Cronbach's alpha coefficients ranging from 0.604 (moderate) to 0.810 (very high), confirming the instrument's consistency and reliability for measuring environmental literacy in educational research contexts.

Procedures

This research employed a systematic series of procedures based on the Lee and Owen (2004) multimedia development model, encompassing the stages of analysis, instructional design, development and implementation, and evaluation. The analysis stage aimed to identify the underlying problems and gaps between the actual and expected conditions in the field. A needs assessment was conducted to recognize the absence of a Learning Management System (LMS)-

based learning medium at SMAN 1 Kragan, as well as to identify students' needs in developing critical thinking and environmental literacy. Furthermore, a front-end analysis was carried out, including audience, technology, task, and media analyses, to determine the appropriate instructional goals and media format. The findings revealed that most students had access to digital devices such as smartphones and laptops, allowing the adoption of a web-based learning environment. The solution proposed was the development of a biodiversity e-learning website (BioDiv Web) that supports structured and interactive learning through the integration of Structured Project-Based Learning (SPjBL) with the Citizen Science Project (CSP) approach.

The instructional design stage focused on confirming the product concept and determining appropriate development methods. The research was scheduled for the 2025/2026 academic year. Media specifications were established, including document type, visual style, language conventions, and layout. The product was designed in a website format using WordPress, with supporting software such as Canva for design, Microsoft Word for content development, and Google Drive for storage. The learning structure was organized in accordance with the *Capaian Pembelajaran* (CP) and the teaching module on biodiversity. The instructional materials included critical thinking test items and environmental literacy instruments. Configuration control was applied to manage the website's structural components using PHP and MySQL. The content creation process included drafting and editing materials in Microsoft Word, integrating visual elements via Canva, and developing the final web format on WordPress.

The development and implementation stage involved transforming the instructional design into a functional digital learning product. During the pre-production phase, a storyboard, interface design, and prototype were created. The production phase combined textual, visual, and interactive components, while the post-production phase included expert validation, product revision, and user testing. Product validation was conducted by experts in media, material, learning instrument expert, and educational practice, followed by individual, small-group, and field trials involving students from SMAN 1 Kragan. The implementation employed a non-randomized control group pretest-posttest design, where the experimental group received SPjBL instruction assisted by BioDiv Web, while the control group received another model without the web support. Data were collected from two classes (X-2 and X-7) involving 70 students from a total population of 355, using validated instruments for critical thinking and environmental literacy. The design of the quasi-experimental study is presented in Table 1.

Table 1. Design of the Quasi-Experimental Study

Group	Pretest	Treatment	Posttest
Experimental (X-2)	O_1	X_1	O_2
Control (X-7)	O_3	X_2	O_4

Description:
X_1 : Structured Project-Based Learning assisted by BioDiv Web
X_2 : Problem-based Learning
O_1 : Pretest score of the experimental class
O_2 : Posttest score of the experimental class
O_3 : Pretest score of the control class
O_4 : Posttest score of the control class

The design allows comparison of learning outcomes between the two groups to evaluate the effectiveness of the developed digital platform in enhancing students' critical thinking and environmental literacy. Finally, the evaluation stage was conducted to measure the validity, practicality, and effectiveness of the BioDiv Web. Evaluation followed Kirkpatrick's (1988) four-level model, encompassing reaction, performance, knowledge, and data analysis. Expert validation scores were analyzed descriptively using percentage criteria adapted from Sulisetijono (2018). The effectiveness testing applied statistical analyses, including normality, homogeneity, and one-way ANCOVA at a 5% significance level. Pretest and posttest scores were further examined using the normalized gain (N-gain) index (Hake, 1998) to determine the level of learning improvement achieved by students after the intervention.

Data Analysis

The data analysis procedures in this study were conducted systematically to evaluate the validity, practicality, implementation, and effectiveness of the BioDiv Web learning platform, as well as to test the research hypotheses. Both descriptive and inferential statistical analyses were applied to ensure a comprehensive interpretation of the data.

Validity and Practicality Testing of BioDiv Web

The validity test aimed to assess the quality of the developed BioDiv Web in terms of content, media design, and pedagogical relevance. Validation involved four experts, namely, a media expert, a material expert, a learning instrument expert, and an educational practitioner. The validators and practitioners were selected based on their relevant expertise. The media expert was a Biology Education lecturer with over five years of experience in developing web-based instructional materials. The material expert, a Biology lecturer with a master's degree and similar experience, validated the conceptual accuracy of the portfolio content. Meanwhile, the practitioner, a Biology teacher with at least five years of teaching experience, provided practical insights for classroom implementation.

Each expert provided evaluations using a Likert-type scale that covered several aspects such as content accuracy, interface design, interactivity, and ease of use. After the quality value is obtained, the feasibility of the BioDiv website can be determined based on the interpretation of the feasibility test value from the adaptation of Sulisetijono (2018). The validity score was calculated using the percentage formula:

$$V.ah = T.se/T.sh \times 100\%$$

Description:
V.ah : Expert validation;
T.se : Total score achieved;
T.sh : Total expected score

The validation result categories can be seen in Table 3.

Table 2. Media Validity Criteria

Range Value	Validity Criteria
100	Highly valid, or the product can be used without any improvement.
$85,00 \leq X \leq 99,99$	Highly valid, or the product can be used with minor improvements.
$70,00 \leq X < 85,00$	Valid, or the product can be used with moderate improvements.
$55,00 \leq X < 70,00$	Less valid, or the product can be used with major improvements.
$40,00 \leq X < 55,00$	Not valid, or the product cannot be used.
$X < 40,00$	Very invalid, or the product cannot be used.

Source: adapted from Sulisetijono (2018:76)

The practicality test measured the feasibility of implementing BioDiv Web in classroom settings. Students' and teachers' responses were analyzed using the same percentage formula. A result above 70% was considered practical, indicating that the platform was easy to access, interactive, and beneficial for learning biodiversity concepts.

Implementation of Structured Project-Based Learning (SPjBL) Syntax

The implementation level of SPjBL syntax through BioDiv Web was analyzed descriptively to determine the extent to which the learning stages were carried out effectively. Observation sheets were used to record the conformity of learning activities with the six SPjBL phases: phase 1: introduction, phase 2: project overview, phase 3: investigation project, phase 4: discussion, phase 5: presentation, and phase 6: reflection. Data on the implementation of the SPjBL model syntax using the CSP approach were obtained from the syntax implementation sheet filled out by teachers (observers). Data analysis for the syntax implementation results can be seen in Table 3.7 and analyzed descriptively in the form of percentages and adjusted to the syntax implementation criteria. The formula used is:

$$P = \frac{\mathrm{A}}{\mathrm{B}}$$

Description:
P : Percentage of syntax implementation
A : Total score obtained
B : Ideal total score

Scores were converted into percentages and categorized as very good (85–100%), good (70–84%), moderate (55–69%), and poor (<55%). The implementation was considered successful if the average syntax execution rate exceeded 70%, signifying that students actively participated in inquiry and project-based investigation using BioDiv Web as a learning medium.

Effectiveness of BioDiv Web

The effectiveness of the developed product was evaluated based on students' improvement in critical thinking skills and environmental literacy. Effectiveness testing was performed using the Normalized Gain (N-Gain) analysis (Hake, 1998) to measure students' learning progress between pretest and posttest scores. The formula used is:

$$Normalize - gain\ (\mathrm{g}) \ = \frac{pretest\ score - posttest\ score}{Maximum\ score - Pretest\ Score}$$

The interpretation of N-Gain values followed Hake's classification: low (<0.3), moderate (0.3–0.7), and high (>0.7).

Hypothesis Testing

Confirming the effectiveness of BioDiv Web statistically, hypothesis testing was conducted using One-Way Analysis of Covariance (ANCOVA) at a 0.05 significance level. ANCOVA was chosen because it allows for the adjustment of pretest scores as a covariate to control for initial differences between groups, thereby isolating the intervention's true effect and increasing statistical precision compared to simple ANCOVA, which ignores baseline disparities (Field, 2013; Pallant, 2020). The pretest scores served as the covariate to control for initial differences between groups. Before ANCOVA, assumptions of normality and homogeneity were tested using the Kolmogorov–Smirnov and Levene's tests, respectively. If the calculated significance value exceeded 0.05, the data were considered normally distributed and homogeneous.

RESULTS

This section presents the findings obtained from the implementation of the research procedures and data analyses. The results are organized to address the research objectives, focusing on the development and effectiveness of the BioDiv Web platform in enhancing students' critical thinking skills and environmental literacy.

Media Expert Validation

The evaluation by media experts revealed an overall mean score of 96.8% after revision, classified as highly valid. The highest aspect scores were obtained in Website Appropriateness and Suitability and User Feasibility for Beginners (100%), reflecting the platform's accessibility and user-centered design. These findings are consistent with prior studies emphasizing usability as a crucial determinant of digital learning tool effectiveness (Harackiewicz & Priniski, 2025). The findings from the media expert validation of the BioDiv Web platform are summarized in Figure 2.

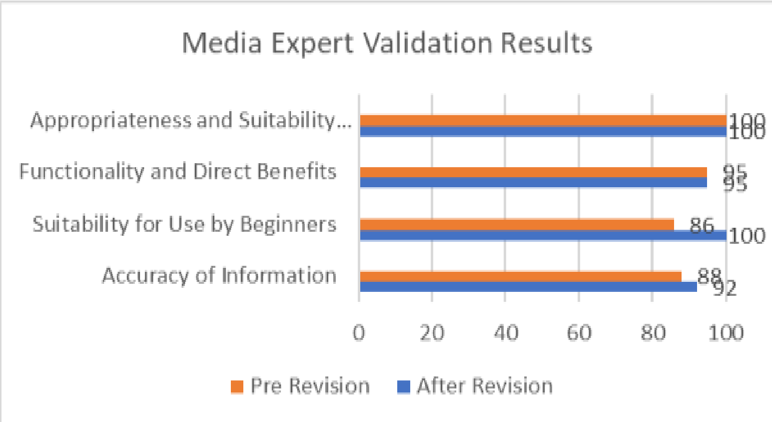

Figure 2. Media expert validation results

Material Expert Validation

The material expert validation achieved an average score improvement from 82% (valid) before revision to 100% (highly valid) after revision. All evaluated aspects, including Content Feasibility, Presentation Standards, and Language Appropriateness, met the highest validation level. This aligns with research emphasizing that well-structured content design enhances conceptual understanding and learner engagement in online biology learning (Demir & Önal, 2021). The findings from the material expert validation of the BioDiv Web platform are summarized in Figure 3.

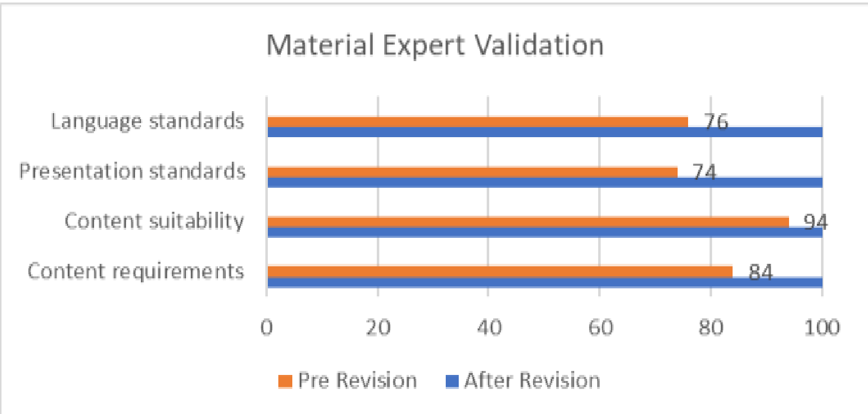

Figure 3. Material Expert Validation

Learning Instrument Expert Validation

The validation by instructional design experts obtained an average score of 91.5%, categorized as highly valid. The aspects of Learning Objectives Alignment, Module Feasibility, critical thinking test items and environmental literacy test and questionnaire were all confirmed to be appropriate for use. This result supports the view that the integration of structured project-based learning with citizen science promotes cognitive and attitudinal development (Finger et al., 2023). The findings from the learning instrument expert validation of the BioDiv Web platform are summarized in Figure 4.

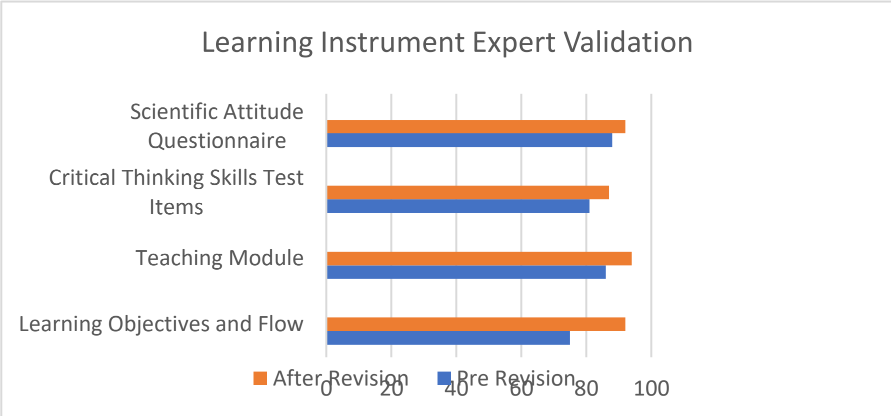

Figure 4. Learning instrument expert validation

Biology Education Practitioner Validation

Feedback from biology education practitioners yielded an average score of 94.6% (highly valid). The highest-rated aspects were Content Appropriateness (100%) and Usability (96%), confirming that BioDiv Web is both pedagogically sound and technically efficient. Prior studies affirm that teacher-based evaluations are essential for ensuring contextual relevance and classroom applicability (Finger et al., 2023). The findings from biology education practitioner validation of the BioDiv Web platform are summarized in Table 3.

Table 3. Biology Education Practitioner Validation

No	Aspects	Score	Category
1	Content Feasibility	100	Highly Valid
2	Presentation Aspect	92	Highly Valid
3	Language Aspect	94	Highly Valid
4	Design and Graphics Aspect	92	Highly Valid
5	Usability Aspect	96	Highly Valid
	Average	94,6	Highly Valid

Individual and Small Group Trials

The individual trial results showed a mean score of 92% (highly practical), while small-group trials resulted in 92.2% (highly practical). These findings suggest that students found the interface intuitive and the learning flow coherent. Usability and student engagement in e-learning environments are pivotal in determining learning persistence and satisfaction (Gunesekera et al., 2019).

Field Trial

The field trial achieved an overall practicality score of 92% (highly practical), indicating that BioDiv Web effectively supports classroom integration and collaborative learning activities in authentic educational contexts. These outcomes reinforce that technology-based approaches can successfully cultivate 21st-century competencies among high school students (Chu et al., 2017; Uyen et al., 2023). The findings from the field trial test are summarized in Figure 5.

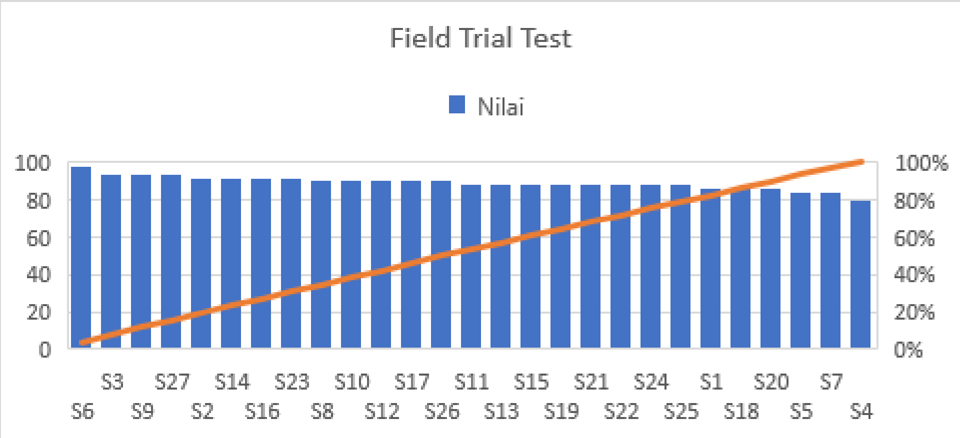

Figure 5. Field trial test results

Student's Critical Thinking Skills

The analysis of students' critical thinking skills showed a substantial improvement in the experimental class (X-3) compared to the control class (X-7). The bar chart illustrating the implementation results of students' critical thinking skills is presented in Figure 6.

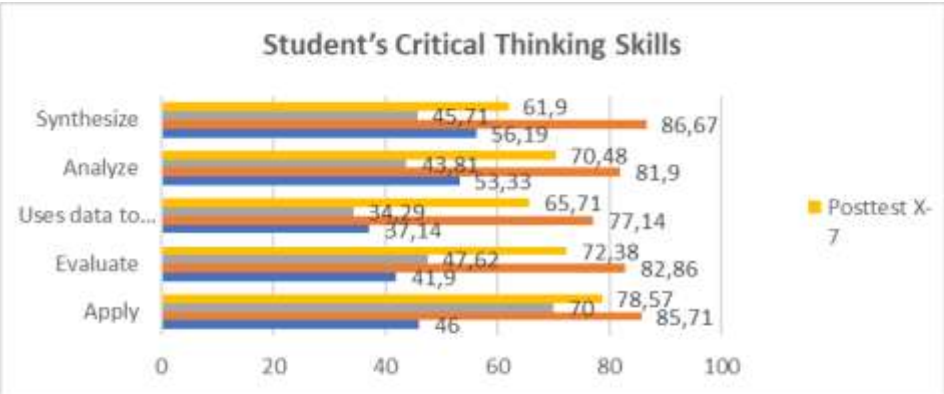

Figure 6. Student's critical thinking skills results

The implementation of SPjBL assisted by BioDiv Web demonstrated a considerable improvement in students' critical thinking performance. The experimental class (X-3) obtained an average pretest score of 49.76% and a posttest score of 83.57%, resulting in an N-gain score of 0.68 (categorized as moderate effectiveness). Meanwhile, the control class (X-7), which was taught using PBL, increased from 48.81% to 70.24%, with an N-gain of 0.40, also in the moderate category. These findings indicate that BioDiv Web effectively facilitates analytical reasoning, data interpretation, and synthesis through contextual biodiversity projects. The results of the prerequisite tests for students' critical thinking skills are presented in Table 4.

The normality test using the Kolmogorov–Smirnov method revealed that the pretest and posttest data for both classes were normally distributed ($p > 0.05$). The Levene's Test for homogeneity also indicated that the data were homogeneous ($p > 0.05$), fulfilling the assumptions for parametric testing. The ANACOVA test results showed a significant difference ($p < 0.05$) between the experimental and control groups after controlling for pretest scores, confirming that

BioDiv Web had a statistically significant impact on improving students' critical thinking skills. This finding supports Sarıgöz, (2023), who emphasized that structured, project-based learning supported by digital media enhances higher-order cognitive processes in science learning.

Table 4. The results of the prerequisite tests for students' critical thinking skills

Prerequisite tests		Significance level	Description
Saphiro-wilk	Pretest Experiment (X-3)	0.917	Normal
	Posttest Experiment (X-3)	0.198	Normal
	Pretest Control (X-7)	0.913	Normal
	Posttest Control (X-7)	0.341	Normal
	Levene's Test	0.325	Homogeneous
	ANACOVA	<0.001	Statically Significance

Students' Environmental Literacy

The implementation of BioDiv Web also improved students' environmental literacy significantly. The experimental group's score increased from 43.38% (low) to 83.70% (high), producing an N-gain of 0.65 (moderate effectiveness). The control group improved from 43.11% to 69.66% (N-gain = 0.33). The most substantial improvements occurred in the indicators of ecological knowledge (N-gain = 0.76) and cognitive skills (0.71), showing that students became more capable of analyzing biodiversity problems and proposing environmentally responsible actions. The bar chart illustrating the implementation results of students' environmental literacy is presented in Figure 7.

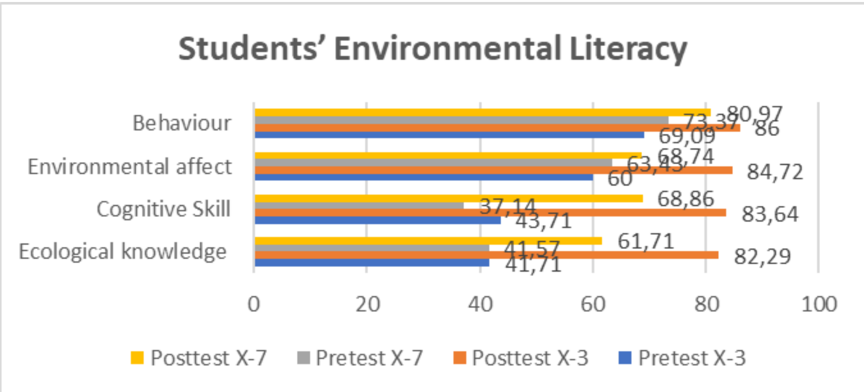

Figure 7. Implementation Results of Students' Environmental Literacy

Table 5. Prerequisite tests for students' environmental literacy

Prerequisite tests		Significance level	Description
Saphiro-wilk	Pretest Eksperimen (X-3)	0.583	Normal
	Posttest Eksperimen (X-3)	0.351	Normal
	Pretest Kontrol (X-7)	0.740	Normal
	Posttest Kontrol (X-7)	0.887	Normal
	Levene's Test	0.363	Homogeneous
	ANACOVA	<0.001	Statically Significance

The results of the Kolmogorov–Smirnov normality test confirmed that the data were normally distributed ($p > 0.05$), and the Levene's test showed homogeneous variance ($p > 0.05$) between groups. The ANCOVA analysis yielded a significant difference ($p < 0.05$) between the experimental and control classes, indicating that BioDiv Web had a meaningful effect on students' environmental literacy outcomes. These results reinforce previous studies by Ardoin et al., (2020), Phillips et al., (2018), and (Monroe et al., 2019), which reported that technology-based citizen science projects improve environmental awareness, ecological understanding, and behavioral engagement in biodiversity conservation. The results of the prerequisite tests for students' environmental literacy are presented in Table 5.

DISCUSSION

This study successfully developed and implemented the BioDiv Web, an e-learning platform integrating Structured Project-Based Learning (SPJBL) and Citizen Science, which proved to be highly valid, practical, and effective in enhancing senior high school students' critical thinking skills and environmental literacy. The discussion interprets these key findings in the context of contemporary educational theory and research.

Validity and Practicality of BioDiv Web

The exceptional validation scores from media experts (96.8%), material experts (100%), and learning design experts (91.5%) confirm that the BioDiv Web platform is theoretically sound and pedagogically robust. The high scores in "Website Appropriateness" and "User Feasibility for Beginners" are critical, as usability is a primary determinant of the successful adoption of digital learning tools (Freire et al., 2012). Furthermore, the "highly practical" ratings from one-to-one trials (92%), small-group trials (92.2%), and the field trial (92%) demonstrate that the platform is not only well-designed but also feasible and easy to use in real classroom settings. This alignment between validity and practicality is essential; a tool can be perfectly designed in theory but fail if it is not practical for its intended users (Koç & Kanadlı, 2025). The high practicality scores suggest that the platform's interface and project flow were intuitive, minimizing cognitive load and allowing students to focus on the learning tasks rather than navigating the technology itself (Sweller et al., 2019).

Table 6. The final development stages are shown in

<table>
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<td>1)


The BioDiv homepage consists of several main components, including navigation buttons and three stripes in the upper right corner containing icons that refer to the website content, such as our project icon, sharing with experts, reflections, LKPD upload icon, and books. The top of the page also contains the website name and a brief description. The explore button contains a brief overview of student activities.</td>
<td>2)


The middle section of the website page contains an overview and nine learning icons consisting of lessons 1 to 9. Each learning icon contains materials, videos, and student worksheets.</td>
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The mind map contains the main points of the material presented on the website. The “Let's Find Out” icon contains the 21st-century skills that students learn through the BioDiv page. These skills include critical thinking and environmental literacy.</td>
<td>4) 

The Assessment icon with the tagline Let's Learn More! contains assessments to measure critical thinking skills, scientific attitudes, and environmental literacy. In addition, this section also contains pre-tests and post-tests that students must complete.</td>
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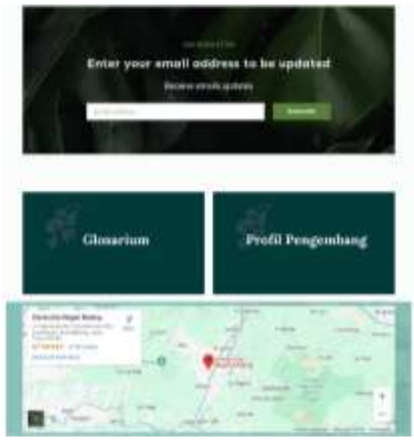
<td>5) 

The Let's explore! icon contains articles and news about local biodiversity that students can access.</td>
<td>6) 

This section contains icons for entering email addresses, so that students always receive updates and notifications about the projects they are working on. Next are icons for the glossary and developer profiles, as well as an icon for a map showing the location where the website is accessed.</td>
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The significant improvement in material expert validation scores from 82% to 100% after revision highlights the importance of incorporating expert feedback to ensure content accuracy and alignment with learning standards. This rigorous validation process ensures that the platform's core content is reliable, which is a prerequisite for fostering accurate scientific understanding (Demir &

Önal, 2021). The endorsement from biology education practitioners (94.6%), particularly in "Content Feasibility" (100%) and "Usability" (96%), provides strong evidence for the platform's contextual relevance. Teachers, as end-users, are best positioned to judge the classroom applicability of an educational innovation, and their positive assessment is a strong predictor of successful implementation (Erviana et al., 2022). Therefore, the convergent validity from multiple experts and the high practicality from users establish a solid foundation for the platform's subsequent effectiveness in improving student learning outcomes.

The developed product, namely BioDiv-Web represents the outcome of this research and development process, is accessible via the following link: https://biodiv.uinws.or.id. The final development stages are shown in Table 6.

Enhancing Critical Thinking through Structured Project-based Learning and Citizen Science Approaches

The implementation of BioDiv Web led to a statistically significant improvement in students' critical thinking skills, with the experimental class achieving a higher N-gain (0.68) compared to the control class (0.40). The ANCOVA results ($p < 0.001$) confirm that this difference was due to the intervention, not pre-existing differences between the groups. This outcome can be attributed to the synergistic effect of the platform's design and the SPjBL model integrated with Citizen Science approaches. The structured project phases compelled students to engage in higher-order cognitive processes. They were not merely learning about biodiversity but were acting as scientists by collecting and analyzing real-world data (Bonney et al., 2009). This authentic inquiry necessitates analysis, evaluation, and synthesis, which are the core components of critical thinking (Facione, 2023).

The data shows notable improvements in specific critical thinking indicators, such as "Evaluate" (N-gain: 72.38 to 82.86) and "Synthesize" (N-gain: 61.9 to 86.67). This suggests that the platform effectively supported students in making judgments based on evidence and combining information to form new conclusions. These skills are directly fostered by the citizen science approach, where students must evaluate the quality of their own and their peers' data and synthesize disparate pieces of information to understand local biodiversity patterns (Peter et al., 2019). The findings align with previous research by Sarıgöz (2023), who found that project-based science learning environments significantly enhance students' analytical and evaluative skills. Moreover, the digital platform provides a scaffolded environment where resources, data tools, and collaborative spaces are integrated, supporting the complex reasoning required for such projects better than traditional, non-digital PBL might (Chu et al., 2017). Thus, BioDiv Web served as a cognitive tool that amplified the inherent potential of SPJBL to foster critical thinking.

Development of Environmental Literacy

The most striking improvement was observed in students' environmental literacy, where the experimental group achieved an N-gain of 0.65 compared to 0.33 in the control group, with ANCOVA confirming a significant effect ($p < 0.001$). The breakdown of the construct is revealing: the highest gains were in "Ecological Knowledge" (N-gain = 0.76) and "Cognitive Skills" (N-gain = 0.71). This pattern strongly indicates that the Citizen Science approach, facilitated by BioDiv Web, was effective in moving students beyond abstract knowledge to applied understanding. By directly observing, documenting, and analyzing local biodiversity, students constructed their own ecological knowledge in a context that was personally relevant (Ardoin et al., 2020). This direct experience is far more powerful for knowledge retention and application than learning from textbooks only.

These findings align with (Noviana et al., 2022) who have demonstrated in their research that digital and contextual approaches can significantly contribute to raising students' environmental literacy. The contextualisation of biodiversity issues and the use of interactive media are argued to deepen students' understanding of ecological concepts and enhance cognitive, affective, and behavioral dimensions of environmental literacy. Besides, the marked improvement in ecological knowledge (N-gain = 0.76) and cognitive skills (N-gain = 0.71) suggests that the BioDiv Web not only delivered content but also facilitated higher-order thinking about biodiversity issues. Mirroring Remindima et al., (2024) assertion that literacy thrives when students engage with real-world environmental contexts, guided inquiry, and reflection.

The progression from knowledge to "Environmental Affect" and "Behaviour" is crucial for true environmental literacy. The data show that students in the experimental group developed stronger affective connections and reported a greater inclination toward pro-environmental behaviors. This aligns with the concept of "connectedness to nature," which is a strong predictor of pro-environmental behavior (Ernst et al., 2017). By engaging in citizen science, students likely developed a stronger personal connection to their local environment, fostering a sense of care and responsibility (Monroe et al., 2019). The platform's project-based structure, which may have included actions like proposing conservation measures, provides a pathway for translating this effect into behavioral intention. This outcome supports the findings of Bonney et al. (2016), who argue that citizen science can foster increased environmental awareness and agency among participants.

Finally, these results imply that designing digital platforms with structured learning phases, problem orientation, observation, investigation, reporting, and reflection can lead to meaningful improvements in environmental literacy, especially when combined with local biodiversity contexts. This reinforces the notion by (Yuswa et al., 2016) that building literacy is not merely about transferring knowledge but about enabling students to navigate, analyse, and act on environmental issues.

CONCLUSION

This study conclusively demonstrates that the BioDiv Web platform, developed through a systematic design-based research approach, successfully integrates Structured Project-Based Learning (SPJBL) with Citizen Science approaches to create an effective digital learning environment. The platform's high validity and practicality establish its robustness as an educational tool. Most significantly, its implementation yields substantial improvements in students' critical thinking skills (N-gain 0.68), scientific attitudes (N-gain 0.51-0.52), and environmental literacy (N-gain 0.65). The research confirms that the synergistic combination of structured project phases, authentic citizen science activities, and digital scaffolding enables students to engage in meaningful scientific inquiry, fostering both cognitive development and affective growth. The novelty of this development lies in the effective orchestration of these three elements: SPJBL syntax, citizen science authenticity, and e-learning functionality. The implications of this research are profound for education and environmental stewardship; educators can adopt BioDiv Web to enhance STEM curricula, policymakers may integrate citizen science into national environmental policies to promote public engagement, and future studies could explore scalability across diverse contexts or long-term impacts on real-world conservation behaviors, ultimately contributing to sustainable development goals.

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