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Integrating Project-Based Learning with iNaturalist to Enhance Biodiversity Literacy

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Abstract: This study investigated the effect of an iNaturalist-assisted Project-Based Learning (PjBL) model on students' biodiversity literacy in the context of biodiversity education. A quasi-experimental method with a nonequivalent control group design was employed. The participants were Grade 10 students at SMA Negeri 8 Tasikmalaya during the 2025/2026 academic year, selected using purposive sampling. The experimental group received iNaturalist-assisted PjBL, the positive control group received PjBL without iNaturalist, and the negative control group received Discovery Learning. Biodiversity literacy was assessed using a validated and reliable 36-item multiple-choice test. The data were analyzed using analysis of covariance (ANCOVA) at a 5% significance level, followed by the Least Significant Difference (LSD) post hoc test. The ANCOVA results demonstrated that the iNaturalist-assisted PjBL model had a significant effect on students' biodiversity literacy ($F = 39.992$, $p < 0.001$). The LSD test further confirmed that the experimental group achieved the highest mean score (32.66), significantly exceeding the PjBL group without iNaturalist assistance (23.85) and the Discovery Learning group (19.73). These findings indicate that integrating citizen science technology into the PjBL framework significantly enhances students' biodiversity literacy. The statistically significant differences among the three groups provide empirical evidence that combining project-based instruction with digital species-identification technology is more effective in facilitating students' mastery of biological concepts than the other instructional approaches examined.
Keywords: Biodiversity; biodiversity literacy; iNaturalist; project-based learning; students

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INTRODUCTION

Twenty-first-century education requires a shift from the mastery of theoretical content toward the development of essential competencies, including scientific literacy, critical thinking, and character development (González-Salamanca et al., 2020; Rios et al., 2020). Within this context, biodiversity literacy is increasingly important because it enables students to understand biological diversity, recognize environmental problems, and develop evidence-based solutions. Biodiversity literacy is particularly relevant amid the accelerating biodiversity crisis because it combines conceptual understanding, species-identification skills, awareness of human–environment relationships, and responsible conservation-oriented action (Barrutia et al., 2023; Fajri et al., 2024).

In this study, biodiversity literacy was conceptualized using the framework proposed by Katili et al. (2021), which comprises four interrelated dimensions: (1) knowledge of biodiversity, (2) attitudes toward biodiversity, (3) identification skills, and (4) pro-environmental behavior. This framework was selected because it connects cognitive understanding with the ability and willingness to engage in biodiversity conservation. For measurement purposes, the cognitive and applied manifestations of these dimensions were operationalized through six indicators covering the definition and utilization of biodiversity, levels of biodiversity, causes of biodiversity loss, conservation principles, conservation strategies, and the communication of solutions to biodiversity-related problems. Compared with broader environmental literacy frameworks, this framework is particularly relevant to contextual biology education at the secondary-school level.

Biodiversity literacy is a fundamental component of contextual biology learning (Fajri et al., 2024). It enables students to obtain accurate information about species and their ecological functions and to apply this information when addressing environmental problems (Barrutia et al., 2023). More specifically, biodiversity literacy involves recognizing when biodiversity information is needed, locating species data in the field, using such information effectively, and critically evaluating conservation status and data sources (Oliveira et al., 2025). These competencies strengthen students' ability to interpret biological information, evaluate scientific evidence, and apply knowledge to environmental decision-making.

Digital technologies have substantially expanded access to biodiversity information. However, greater access does not necessarily ensure that students can select, interpret, and verify such information accurately. Students therefore require the skills to distinguish credible biodiversity records from incomplete or inaccurate data and to use digital information responsibly. Accordingly, biodiversity literacy is essential in secondary education because it supports scientific inquiry, promotes critical evaluation of biological data, and strengthens students' awareness of and participation in conservation efforts (Fajri et al., 2024; Oliveira et al., 2025).

Despite its importance, biodiversity literacy remains difficult to develop through conventional classroom instruction. Previous studies have shown that students are often inadequately prepared to manage the complexity of scientific identification and experience difficulty locating and evaluating reliable information about the biodiversity in their local environments (Barrutia et al., 2023; Clark & Hsu, 2023). Many students also lack the skills required to identify appropriate academic references concerning local flora and fauna. This concern is consistent with Indonesia's broader scientific-literacy performance. In PISA 2022, only 34% of Indonesian students attained at least Level 2 proficiency in science, compared with an OECD average of 76%, indicating that many students experience difficulty applying scientific knowledge and evaluating evidence in familiar situations (OECD, 2023).

Empirical evidence from Indonesia also indicates substantial gaps in students' understanding of biodiversity. Adriyawati et al. (2020) reported that low environmental literacy was associated with limited opportunities for students to interact directly with local ecosystems. Similarly, Fajri et al. (2024) found that inadequate species-identification skills contributed to limited awareness of conservation issues. This problem was also observed at SMA Negeri 8 Tasikmalaya, where a preliminary assessment yielded an average biodiversity literacy score of 14, which was classified as very low according to the assessment criteria. This finding suggests that students had not yet developed an adequate understanding of biodiversity concepts or the ability to apply these concepts to local environmental problems. Such limited literacy may result from learning processes that are insufficiently contextual and excessively focused on memorizing taxonomic terminology, thereby preventing students from recognizing the ecological significance and conservation value of local biodiversity (Aslan Efe & Efe, 2022; Barrutia et al., 2023).

Addressing this problem requires pedagogical strategies that engage students in authentic scientific inquiry. Project-based learning integrated with inquiry-oriented activities provides a potentially effective approach to developing scientific literacy and problem-solving skills (Perdana et al., 2023). Project-based learning (PjBL) organizes learning around meaningful questions or problems that students investigate collaboratively through the development of an authentic project (Adriyawati et al., 2020). Compared with conventional instruction, PjBL can promote active engagement, independent learning, collaboration, and critical thinking by requiring students to collect, analyze, and communicate evidence (Hudha et al., 2023).

The stages of PjBL can directly support the development of biodiversity literacy. Formulating an essential question stimulates curiosity and encourages students to recognize a biodiversity-related problem. Designing a project plan supports the construction of conceptual knowledge, whereas implementing and monitoring the project provides opportunities to practice observation, data collection, and species identification. Project evaluation and reflection enable students to assess the quality of their evidence, communicate their findings, and formulate conservation-oriented solutions. Thus, PjBL provides a pedagogical structure through which biodiversity knowledge can be connected to identification practices, scientific reasoning, and environmental action.

Nevertheless, project activities alone may not be sufficient when students lack valid and accessible tools for identifying organisms and verifying biodiversity data (Hussein, 2021). The integration of citizen science technology through iNaturalist can complement PjBL by connecting classroom learning with authentic biodiversity observation. iNaturalist enables users to document organisms using photographs, locations, and observation dates; obtain computer-generated identification suggestions; and receive feedback from a global community of users and taxonomic experts (Aristeidou et al., 2021; Hitchcock et al., 2021; Stevenson et al., 2021).

The platform supports several dimensions of biodiversity literacy. Its Computer Vision feature assists students during initial species identification, while observation records provide access to taxonomic and distributional information. Community-based verification encourages students to review and revise their identifications, thereby promoting scientific responsibility. In addition, observations that meet data-quality requirements can contribute to broader biodiversity databases and research activities (Aristeidou et al., 2021; Hitchcock et al., 2021). Evidence from biodiversity citizen science indicates that participation may support gains in scientific knowledge, inquiry skills, environmental self-efficacy, interest, motivation, and pro-environmental behavior (Peter et al., 2021).

The use of iNaturalist in education can therefore transform students from passive recipients of biological information into active contributors to biodiversity knowledge. By documenting local organisms, students can organize species information, improve their taxonomic knowledge, and generate authentic biodiversity data (Niemiller et al., 2021). The platform also supports collaborative learning because students can compare observations, discuss uncertain identifications, and receive feedback from users beyond the classroom. These processes may increase motivation and make environmental exploration more scientifically meaningful.

Integrating iNaturalist into PjBL is theoretically valuable because the two approaches serve complementary functions. PjBL provides the instructional structure for investigating an authentic problem, whereas iNaturalist provides the technological infrastructure for collecting, organizing, identifying, validating, and communicating biodiversity data. Students can therefore investigate local biodiversity through a systematic project while simultaneously participating in citizen science. This integration is particularly relevant in Indonesia, a megabiodiverse country that requires an ecologically literate generation capable of contributing to the sustainable management of its biological resources. Limited environmental awareness and insufficient knowledge of local biodiversity may weaken public participation in conservation and contribute to continuing environmental degradation (Fajri et al., 2024).

Although PjBL and digital technology have been widely applied in science education, several research gaps remain. First, previous PjBL studies have predominantly examined general scientific literacy, critical thinking, or learning outcomes rather than biodiversity literacy as a specific construct. Second, educational applications of iNaturalist have been investigated more frequently in higher education than in secondary-school biology. Third, relatively few studies have integrated iNaturalist systematically into the stages of PjBL within the Indonesian secondary-school curriculum. Finally, previous research has rarely compared iNaturalist-assisted PjBL, PjBL without iNaturalist, and Discovery Learning simultaneously within a single quasi-experimental design.

The present study addresses these gaps by integrating a citizen science approach through iNaturalist into PjBL and comparing its effects with those of PjBL without iNaturalist and Discovery Learning. The study also assesses biodiversity literacy using six indicators that represent students' abilities to understand biodiversity concepts, analyze biodiversity loss, evaluate conservation strategies, and communicate solutions to biodiversity-related problems. This design allows the contribution of iNaturalist to be distinguished from the contribution of PjBL itself.

Accordingly, this study examined the effect of iNaturalist-assisted PjBL on the biodiversity literacy of Grade X students studying biodiversity at SMA Negeri 8 Tasikmalaya. The outcomes of the iNaturalist-assisted PjBL group were compared with those of a PjBL group without iNaturalist and a Discovery Learning group. It was hypothesized that students who participated in iNaturalist-assisted PjBL would demonstrate significantly higher biodiversity literacy after their initial literacy scores were statistically controlled than students participating in the other two learning conditions.

METHOD

This study employed a quasi-experimental method using a nonequivalent control group design, as illustrated in Figure 1. The independent variable was the instructional model, whereas the dependent variable was students' biodiversity literacy. Three instructional conditions were examined: iNaturalist-assisted Project-Based Learning (PjBL), PjBL without iNaturalist, and Discovery Learning.

The study population comprised all Grade 10 students at SMA Negeri 8 Tasikmalaya during the 2025/2026 academic year. The research sample was selected through purposive sampling based on school administrative considerations, the comparability of students' initial characteristics, daily assessment scores, and levels of classroom participation. To minimize potential bias, all classes were taught by the same teacher and received comparable learning facilities and schedules.

The participants comprised 33 students in the iNaturalist-integrated PjBL class as the experimental group, 33 students in the PjBL class as the positive control group, and 33 students in the Discovery Learning class as the negative control group. The primary difference among the treatments concerned the biodiversity identification process. The experimental group used iNaturalist to identify organisms, whereas the PjBL group conducted identification through online searches and group discussions without using a specialized application. The Discovery Learning group developed biodiversity concepts through the prescribed discovery-learning stages. All groups received equivalent content and instructional time, ensuring comparable content depth and cognitive load.

Table 1. Research design

Group	Pretest	Treatment	Posttest
Experimental	O1	X1	O2
Positive Control	O3	X2	O4
Negative Control	O5	X3	O6

Source: Sugiyono (2023)

Students' biodiversity literacy was measured using a 36-item multiple-choice test. The items were developed based on the biodiversity literacy framework adapted from Katili et al. (2021). The test covered six indicators: defining biodiversity, understanding levels of biodiversity, analyzing the causes of biodiversity loss, understanding conservation principles, identifying conservation efforts, and formulating solutions to environmental crises.

The biodiversity literacy test was reviewed by a biology education expert to establish its logical and content validity. Its empirical validity and reliability were subsequently evaluated through a pilot test administered to students who were not included in the research sample. Analysis using the Anates software yielded a reliability coefficient of 0.90, indicating that the instrument had high reliability.

The study began with the administration of a pretest to all groups to determine students' initial biodiversity literacy. The instructional activities focused on biodiversity and were designed to strengthen students' environmental awareness and ability to explore information through authentic problem-solving experiences.

In the iNaturalist-assisted PjBL class, students were required to create iNaturalist accounts as their digital identities as citizen scientists. They conducted direct observations of flora and fauna within and around the school environment to collect authentic species data. The observed biodiversity included lower plants, flowering plants, and locally occurring insects. Students uploaded photographs of the specimens to iNaturalist, which automatically recorded the geographic coordinates and time of each observation. They then used the platform's artificial intelligence-based identification suggestions and awaited verification from the global community of users and experts to validate the accuracy of the species identifications. The verified observations were subsequently incorporated into the project reports as authentic evidence for addressing local biodiversity problems.

The positive control group followed the same PjBL stages. However, the identification process was conducted manually through online searches and group discussions without the support of the iNaturalist digital platform. Consequently, this group required more time to validate the collected data than the experimental group. In the negative control group, Discovery Learning was implemented through the stages of stimulation, problem identification, data collection, data processing, verification, and conclusion drawing, with an emphasis on independently discovering biodiversity concepts. At the end of the intervention, a posttest was administered, and the resulting data were analyzed to determine the effects of the three instructional models on students' biodiversity literacy.

The data were analyzed using inferential statistics. Preliminary assumption tests included the Kolmogorov–Smirnov test for data normality and Levene's test for homogeneity of variance. Posttest scores were analyzed using analysis of covariance (ANCOVA), with pretest scores included as a covariate. The Least Significant Difference (LSD) post hoc test was subsequently conducted to identify significant differences in mean scores among the three treatment groups.

RESULTS AND DISCUSSION

Biodiversity literacy was assessed through a posttest covering six key indicators. Figure 2 compares students' performance across the iNaturalist-assisted Project-Based Learning (PjBL), PjBL, and Discovery Learning groups.

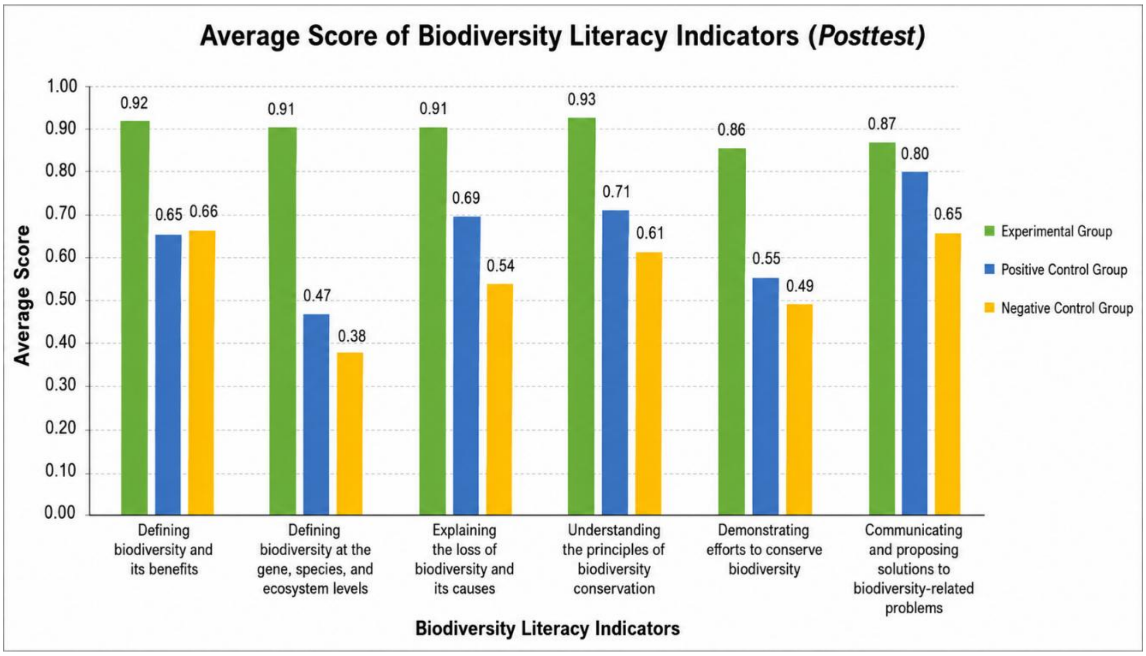

Figure 1. Mean posttest scores for biodiversity literacy indicators

As shown in Figure 1, the experimental group consistently achieved higher biodiversity literacy scores than the positive and negative control groups across all indicators. The experimental group's mean indicator scores ranged from 0.86 to 0.93, with the highest score obtained for understanding biodiversity conservation principles (0.93). By comparison, the highest scores recorded in the positive and negative control groups were 0.80 and 0.66, respectively. Before conducting the ANCOVA, the assumptions of normality and homogeneity of variance were examined using the Kolmogorov–Smirnov and Levene's tests, respectively. The results are summarized in Table 2.

Table 2. Results of the assumption tests for biodiversity literacy

Measure	N	Kolmogorov–Smirnov Sig.	Levene's Test Statistic	Sig.
Biodiversity literacy pretest	99	0.091	1.631	0.201
Biodiversity literacy posttest	99	0.088	1.342	0.175

Table 2 shows that the pretest and posttest data were normally distributed according to the Kolmogorov–Smirnov test ($p > 0.05$) and had homogeneous variances according to Levene's test ($p > 0.05$). ANCOVA was subsequently performed to examine differences in biodiversity literacy among the instructional groups while controlling for pretest scores. The results are presented in Table 3.

Table 3. ANCOVA results for biodiversity literacy

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	2,895.877[a]	3	965.292	26.671	<0.001
Intercept	7,892.385	1	7,892.385	218.069	<0.001
Pretest score	46.053	1	46.053	1.272	0.262

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Group	2,894.768	2	1,447.384	39.992	<0.001
Error	3,546.829	96	36.946		
Total	69,503	99			
Corrected Total	6,442.706	98			

The ANCOVA results indicate that pretest scores, included as a covariate, did not significantly predict students' final biodiversity literacy scores, $F = 1.272$, $p = 0.262$. This finding suggests that differences in initial ability had no statistically significant effect on the posttest outcomes. In contrast, the instructional group had a significant effect on biodiversity literacy, $F = 39.992$, $p < 0.001$. Thus, students' biodiversity literacy differed significantly according to the instructional model implemented. A Least Significant Difference (LSD) post hoc test was then conducted to identify specific differences among the three groups (Table 4).

Table 4. Results of the least significant difference post hoc test

Group	Pretest	Posttest	Difference	Score Increase	Mean Score	LSD Group
iNaturalist-assisted PjBL	10.79	32.66	21.87	202.69%	32.66	a
PjBL	16.06	23.85	7.79	48.51%	23.85	b
Discovery Learning	11.76	19.73	7.97	67.77%	19.73	c

The LSD results placed the iNaturalist-assisted PjBL group (32.66; group a), the PjBL group (23.85; group b), and the Discovery Learning group (19.73; group c) in significantly different categories. In addition to its statistical significance, the effect of iNaturalist-assisted PjBL was reflected in the magnitude of the score increase. The experimental group improved by 21.87 points (202.69%), compared with 7.79 points (48.51%) in the PjBL group and 7.97 points (67.77%) in the Discovery Learning group. These findings indicate that integrating iNaturalist strengthened the effectiveness of PjBL in developing students' biodiversity literacy.

Overall, the combination of PjBL and iNaturalist produced markedly higher posttest scores than either PjBL without iNaturalist or Discovery Learning. The significant ANCOVA result supports the contribution of citizen science technology to students' learning outcomes. The findings suggest that combining structured project work with digitally supported field investigations provides more substantial opportunities for students to develop biodiversity literacy than project-based instruction without iNaturalist or Discovery Learning. Figure 2 presents an example of students' field observations recorded through iNaturalist.

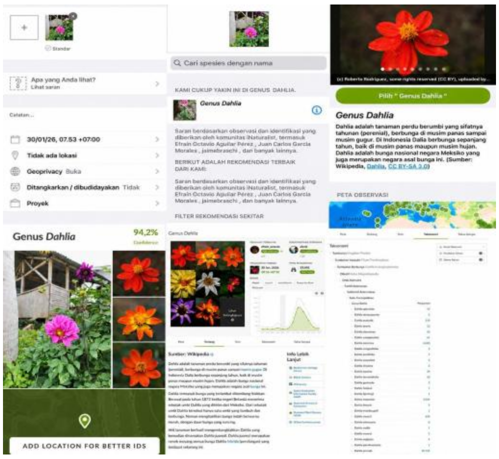

Figure 2. Examples of field observations recorded using iNaturalist

Figure 2 illustrates the authentic observational data that formed the empirical basis of students' biodiversity investigations. The computer vision and community-verification features of iNaturalist connected students' visual observations with more accurate taxonomic identification, thereby directly supporting their identification skills and biodiversity knowledge. The relatively efficient validation process also allowed students in the experimental group to devote more time to analyzing ecological relationships among species. This cognitive and procedural efficiency may have contributed to their higher biodiversity literacy scores. Field investigations and data-analysis activities within the projects also encouraged students to develop critical thinking skills in understanding biodiversity (Fajri et al., 2024).

The integration of scientific activities and citizen science technology strengthened students' biodiversity literacy by combining field-based projects with digital species-identification tools. This finding is consistent with Desmira et al. (2025) and Zhang & Ma (2023), who reported that technology-enhanced PjBL can improve information retention and academic learning outcomes. Technology-supported direct experiences may also strengthen students' emotional and cognitive engagement with learning materials (Chang et al., 2024). Although all three instructional models increased biodiversity literacy, project-based approaches have been reported to be particularly effective in promoting classroom biodiversity learning (Adriyawati et al., 2020). In the present study, iNaturalist-assisted PjBL produced the largest improvement because its instructional stages consistently engaged students with each biodiversity literacy indicator throughout the learning process.

The advantages of iNaturalist-assisted PjBL were evident across all six indicators: defining biodiversity and its uses; distinguishing biodiversity at the genetic, species, and ecosystem levels; explaining biodiversity loss and its causes; understanding biodiversity conservation principles; distinguishing among conservation strategies; and communicating and formulating solutions to biodiversity-related problems. The experimental group achieved the highest scores across these indicators, ranging from 0.86 to 0.93. In comparison, scores ranged from 0.47 to 0.80 in the PjBL group and from 0.38 to 0.66 in the Discovery Learning group.

These results indicate that integrating iNaturalist into project-based learning not only improved conceptual understanding but also strengthened students' ability to access, evaluate, and communicate biodiversity information. Katili et al. (2021) emphasized that biodiversity literacy extends beyond conceptual knowledge to include the ability to apply that knowledge when interpreting environmental problems and developing appropriate solutions. Therefore, biodiversity literacy cannot be developed solely through theoretical instruction. It requires learning experiences that allow students to interact directly with biodiversity and process the resulting information scientifically.

The highest experimental-group score was obtained for understanding biodiversity conservation principles (0.93), followed by defining biodiversity and its uses (0.92) and distinguishing biodiversity at the genetic, species, and ecosystem levels (0.91). These results indicate that students developed a strong conceptual understanding of biodiversity. The ability to define biodiversity is fundamental because an understanding of basic concepts supports students' subsequent analysis of environmental problems.

In iNaturalist-assisted PjBL, students developed biodiversity concepts through direct observation, identification, and documentation of organisms in the school environment. These experiences helped them connect abstract concepts with observable biological objects, making learning more meaningful. This interpretation is consistent with Piaget's constructivist theory, which proposes that individuals actively construct knowledge through interactions with their environment (Piaget & Inhelder, 1972). Through direct observation and species identification, students constructed new understandings from their experiences, thereby promoting more meaningful and potentially longer-lasting conceptual learning.

Knowledge construction through direct experience is also consistent with the learner-centered characteristics of PjBL. Investigations of the local environment enabled students to connect scientific knowledge with ecological conditions encountered in everyday life. Biodiversity was therefore understood not merely as a collection of biological terms but as an observable phenomenon (Al-Qoyyim & Kurniawan, 2025; Nurhidayah et al., 2021). At the same time, iNaturalist's species-identification features helped students recognize organismal characteristics more accurately. By comparing field observations with scientific information available through the application, students could more readily distinguish among genetic, species, and ecosystem diversity.

This process is consistent with situated learning theory, which emphasizes that knowledge is more effectively understood when it is learned in the authentic context in which it is applied (Lave & Wenger, 1991). Identifying biodiversity in the school environment allowed students to learn biodiversity concepts in real-world settings and increased the relevance of the material to their daily lives.

The experimental group achieved a score of 0.91 for distinguishing biodiversity at the genetic, species, and ecosystem levels, compared with 0.47 in the PjBL group and 0.38 in the Discovery Learning group. This substantial difference highlights the importance of direct organism-identification experiences in developing an understanding of biodiversity levels. Rather than merely memorizing textbook definitions, students observed variation among organisms encountered in the field. This process enabled them to connect classification concepts with actual biological conditions and develop a more concrete understanding. These findings are supported by Heberling & Isaac (2018) and Unger et al. (2020), who reported that citizen science technology can increase students' engagement in biodiversity observation and facilitate more concrete conceptual learning.

In addition to improving conceptual knowledge, iNaturalist-assisted PjBL enhanced students' ability to explain biodiversity loss and its causes. The experimental group scored 0.91 on this indicator, compared with 0.69 in the PjBL group and 0.54 in the Discovery Learning group. These results indicate that students were better able to identify relationships among environmental conditions, human activities, and local biodiversity change. This ability is an essential component of biodiversity literacy because students must understand not only the existence of biodiversity but also the threats that contribute to its decline.

The improvement in this indicator can be attributed to the authentic data students obtained through field observations and species documentation using iNaturalist. Directly collected data provided a more contextual learning experience than information obtained exclusively from textbooks or visual media. When students observed variations in organism distribution across specific locations, they were encouraged to analyze the factors influencing species occurrence. This analytical process supported their understanding of biodiversity loss and its effects on ecosystem stability.

Maspul (2024) similarly suggested that direct organism-identification experiences can strengthen students' understanding of relationships between species and environmental conditions because knowledge is developed from authentic experience rather than from visual representations alone. This finding can also be explained through experiential learning theory, which places concrete experience at the center of knowledge development (Kolb, 1984). Direct observations, species documentation, and reflection on field findings enabled students to transform practical experiences into conceptual understanding of biodiversity and the factors affecting it.

Understanding biodiversity conservation principles received the highest score among the six indicators. This finding suggests that project-based experiences enabled students to identify and evaluate alternative conservation actions based on observed environmental conditions. Biodiversity literacy involves not only recognizing environmental problems but also determining appropriate responses. Students must therefore be able to assess the relevance and potential effectiveness of different conservation strategies before making decisions.

PjBL activities provided opportunities for students to collect information, discuss possible solutions, and evaluate the advantages and limitations of different conservation measures. These processes developed critical thinking and decision-making skills, both of which are central to biodiversity literacy. Oliveira et al. (2025) noted that the critical use of information requires individuals to select relevant evidence and apply it in decision-making. The present findings also align with Ortiz (2023) and Shawon et al. (2025), who identified field observation as an effective approach to environmental literacy because it allows students to analyze actual environmental conditions.

The collaborative nature of the project is also consistent with Vygotsky's social constructivist theory, which emphasizes the importance of social interaction in learning (Vygotsky et al., 1978). Through discussion and collaboration, students exchanged information, provided feedback, and developed shared understandings of biodiversity issues. These interactions strengthened their ability to evaluate evidence and formulate solutions.

The experimental group also achieved a high score for distinguishing among biodiversity conservation strategies (0.86), compared with 0.55 in the PjBL group and 0.49 in the Discovery Learning group. This result indicates that students not only understood conservation in general terms but could also assess the appropriateness and effectiveness of different conservation actions in relation to specific environmental problems. This ability developed as students repeatedly verified species identifications and biodiversity data throughout the project. The identification and community-verification features of iNaturalist provided more accurate information, allowing students' evaluations to be grounded more firmly in scientific evidence.

For the indicator concerning the communication and formulation of solutions to biodiversity problems, the experimental group scored 0.87, compared with 0.80 in the PjBL group and 0.65 in the Discovery Learning group. This finding indicates that students could integrate knowledge acquired during their investigations to propose relevant solutions to biodiversity-related problems. The ability to communicate solutions represents an advanced component of biodiversity literacy because students must synthesize available knowledge and evidence to formulate actions that can be applied in real-world contexts.

Digital documentation supported this process by enabling students to organize observational evidence systematically. Biodiversity data collected through iNaturalist provided a basis for constructing stronger arguments and more evidence-based solutions. Consequently, the proposed solutions were supported not merely by assumptions or personal opinions but by empirical findings generated during the project. These results are consistent with Akhyar et al. (2024), Alandita and Lestari

(2024), and Dea Debora Losoh et al. (2025), who found that technology-supported exploration of local environments can improve students' ecological understanding and their ability to design appropriate conservation actions.

Although the Discovery Learning group achieved lower biodiversity literacy scores across all indicators, this result does not imply that Discovery Learning is inherently ineffective. Discovery Learning remains an active instructional model that encourages students to construct concepts independently. The difference lies in the demands of biodiversity learning, which often requires direct interaction with biological objects. In the present study, discovery activities relied primarily on analyzing available information and learning resources, limiting students' opportunities to identify species directly. Consequently, their learning experiences may not have fully supported all dimensions of biodiversity literacy, particularly organism recognition, environmental evaluation, and the development of field-data-based solutions (Muhali et al., 2021).

This study contributes to the development of biodiversity education at the secondary-school level. Previous research has generally focused on the effectiveness of PjBL in improving learning outcomes, critical thinking, or environmental literacy. However, studies specifically integrating iNaturalist into PjBL to improve biodiversity literacy remain limited, particularly in Indonesian biology education. The present findings demonstrate that citizen science technology can strengthen multiple dimensions of biodiversity literacy, including conceptual understanding, biodiversity identification, analysis of threats, evaluation of conservation strategies, and communication of solutions.

The effectiveness of this approach is closely related to the characteristics of iNaturalist as a citizen science platform. Students participated not only as users of biodiversity information but also as contributors of biodiversity data. Uploaded observations could be reviewed by other users and experts, providing students with authentic experience in scientific practice (Aristeidou et al., 2021; Hitchcock et al., 2021). The processes of collecting, validating, and interpreting data encouraged students to use empirical evidence when examining biodiversity in their local environment. Learning therefore progressed beyond conceptual mastery toward the ability to generate, evaluate, and communicate biodiversity information scientifically, which constitutes a central component of biodiversity literacy (Heberling & Isaac, 2018; Niemiller et al., 2021; Unger et al., 2020).

Overall, the integration of PjBL and iNaturalist improved biodiversity literacy more effectively than PjBL without the application or Discovery Learning. This improvement resulted from authentic learning experiences involving field observations, species identification, biodiversity-data analysis, evaluation of environmental problems, and the formulation of evidence-based solutions. These activities supported the development of the biodiversity literacy dimensions described by Katili et al. (2021).

The findings also have important implications for twenty-first-century biodiversity education. Biodiversity instruction should extend beyond the transmission of theoretical information and provide students with opportunities to interact directly with their environment and use digital tools in scientific investigations. Integrating PjBL with iNaturalist demonstrates that citizen science technology can support the development of critical thinking, data literacy, environmental problem-solving, and evidence-based decision-making. This approach therefore represents a relevant instructional alternative for preparing students to participate actively and responsibly in biodiversity conservation.

CONCLUSION

The findings demonstrate that iNaturalist-assisted Project-Based Learning (PjBL) had a significant effect on students' biodiversity literacy and was more effective than both conventional PjBL and Discovery Learning. The integration of citizen science technology, field-based experiences, and project-based learning supported the development of biodiversity literacy more comprehensively. These findings indicate that incorporating iNaturalist into biology instruction may serve as a relevant and effective strategy for strengthening students' biodiversity literacy in the context of twenty-first-century education.

RECOMMENDATION

This study provides evidence that iNaturalist-assisted Project-Based Learning influences students' biodiversity literacy more effectively than PjBL without iNaturalist and Discovery Learning. The integration of authentic projects and digital identification technology also facilitated the development of twenty-first-century competencies represented by the 6Cs: Character, Citizenship, Critical Thinking, Creativity, Collaboration, and Communication. These competencies were fostered through authentic field observations and collaborative project activities.

Nevertheless, the study was limited by the location and duration of the field observations, which restricted the extent to which the full potential of the instructional model could be explored. Future studies should therefore expand the observation area beyond the school environment and extend the duration of the project. These improvements may optimize project outcomes and further strengthen students' mastery of twenty-first-century skills required to address future environmental challenges.

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