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Integration of Project-Based Learning and STEM for Climate Change Education toward the UN SDGs

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ABSTRACT

Climate change education requires learning approaches that not only enhance conceptual understanding but also develop climate literacy in an integrated manner. This study aimed to investigate the effects of STEM-integrated Project-Based Learning (PjBL–STEM) on ecological concept mastery and climate literacy among prospective elementary school teachers. In this study, climate literacy was operationalised as students' ability to understand climate change concepts, analyse climate-related information, evaluate environmental impacts, and formulate mitigation and adaptation strategies. A quasi-experimental pretest–posttest control group design was employed, involving 72 students enrolled in an Environmental Education course, comprising an experimental group ($n = 36$) and a control group ($n = 36$). Data were collected using validated essay-based assessments and analysed using N-gain, independent-samples t-tests, and Multivariate Analysis of Variance (MANOVA). The results showed that the PjBL–STEM group achieved higher learning gains in ecological concept mastery (N-gain = 0.35, moderate) and climate literacy (N-gain = 0.42, moderate) than the control group. Independent-samples t-tests revealed significant differences between groups for both variables ($p < .05$). Furthermore, MANOVA revealed a significant multivariate effect of the learning model on the combined dependent variables, Wilks' $\Lambda = 0.688$, $F(2,69) = 15.42$, $p < .001$, partial $\eta^2 = .312$, indicating a substantial effect of PjBL–STEM on ecological concept mastery and climate literacy simultaneously. These findings suggest that PjBL–STEM provides an effective framework for promoting ecological understanding and climate literacy through authentic, inquiry-based, and interdisciplinary learning experiences. Therefore, PjBL–STEM has the potential to support climate change education and contribute to achieving SDG 4 (Quality Education) and SDG 13 (Climate Action).

INTRODUCTION

Twenty-first-century education requires a paradigm shift from an emphasis on content mastery and rote memorisation towards the development of critical, creative, communicative, and collaborative competencies, alongside responsible attitudes and behaviours in response to global challenges. Among these challenges, climate change has emerged as one of the most urgent issues facing humanity. Its impacts extend beyond environmental degradation, affecting food security, public health, biodiversity, human well-being, and socio-economic stability worldwide. Consequently, individuals require not only scientific knowledge but also the capacity to understand, evaluate, and respond to climate-related challenges in informed and responsible ways. In this regard, climate change education has become increasingly important for preparing younger generations to understand climate-related issues, participate in evidence-based decision-making, and contribute to sustainable solutions (Maurer et al., 2020; OECD, 2023; UNESCO, 2017). At the higher education level, particularly in Islamic Elementary School

Teacher Education (PGMI) programmes, climate change education is of strategic importance because prospective teachers will play a key role in introducing environmental values and sustainability-oriented practices to future generations. Teachers are expected not only to understand climate change conceptually but also to possess the climate literacy needed to translate scientific knowledge into meaningful learning experiences for primary school students. Climate literacy refers to an individual's ability to understand the causes and consequences of climate change, interpret climate-related information, evaluate scientific evidence, make informed decisions, and engage in mitigation and adaptation actions. Therefore, climate literacy extends beyond factual knowledge and encompasses cognitive, affective, and behavioural dimensions that support responsible environmental action.

The development of climate literacy is closely linked to mastery of ecological concepts. Climate change is fundamentally an ecological phenomenon resulting from complex interactions among organisms, ecosystems, and environmental systems. Understanding ecological concepts such as organism-environment interactions, ecosystem balance, biodiversity, energy flow, biogeochemical cycles, and human impacts on ecosystems provides the scientific foundation necessary for explaining climate-related processes and their consequences. Students with strong ecological understanding are more likely to analyse environmental issues from a systems perspective, recognise interdependencies within ecological systems, and evaluate appropriate climate mitigation and adaptation strategies. Conversely, limited ecological understanding may lead to fragmented interpretations of climate change and misconceptions regarding its causes and impacts (Bashirun et al., 2023; Botella et al., 2022). Consequently, mastery of ecological concepts can be considered a foundational component of climate literacy.

Despite this theoretical relationship, previous studies have reported that ecological concepts and climate change are frequently taught as separate and decontextualised topics. Such fragmentation makes it difficult for pre-service teachers to connect ecological knowledge with climate-related phenomena encountered in everyday life (Khaerudin et al., 2025; Lestari, 2022). As a result, students often demonstrate limited climate literacy and insufficient systems-thinking skills for understanding the complexity of environmental challenges (Giac et al., 2025; Trott & Weinberg, 2020). Conventional learning approaches that rely heavily on lectures and memorisation tend to reinforce the gap between conceptual knowledge and real-world environmental issues, even though climate change education requires contextual, inquiry-based, and problem-oriented learning experiences (Trott & Weinberg, 2020).

One promising approach for addressing these challenges is the integration of Science, Technology, Engineering, and Mathematics (STEM). STEM education promotes interdisciplinary learning and encourages students to apply scientific knowledge to authentic problems. Within climate change education, STEM enables students to analyse environmental data, understand ecological system dynamics, and design sustainability-oriented solutions. Previous studies have consistently demonstrated that STEM-based learning enhances conceptual understanding, critical thinking, problem-solving abilities, and scientific literacy, particularly in environmental and sustainability contexts (Chang, 2023; Sofyan, 2021). Furthermore, the Project-Based Learning (PjBL) model has also been shown to be effective in iProject-Based Learning (PjBL) has been shown to improve student engagement, motivation, conceptual understanding, and environmental awareness through active participation in authentic investigations and solution-oriented projects (Giac et al., 2025; Yusuf et al., 2021).

Although studies on STEM and PjBL have increased substantially, several important gaps remain. First, most existing studies have investigated STEM or PjBL separately and have primarily focused on outcomes such as scientific literacy, environmental awareness, critical thinking, or problem-solving skills. Second, within climate change education, previous research has largely emphasised environmental attitudes and awareness, while the relationship between ecological concept mastery and climate literacy has received limited empirical attention. Third, relatively few studies have focused on prospective primary school teachers, despite their strategic role in fostering climate awareness among future generations. Consequently, there is insufficient evidence regarding the effectiveness of integrated pedagogical approaches in simultaneously developing ecological understanding and climate literacy among pre-service teachers.

To address these gaps, this study investigates the integration of Project-Based Learning and STEM within the context of climate change education. The novelty of this study lies in three aspects. First, it integrates PjBL, STEM, and climate change education within a single instructional framework. Second, it focuses on prospective primary school teachers, a population that remains underrepresented in climate change education research. Third, it simultaneously examines ecological concept mastery and climate literacy as interconnected learning outcomes, based on the premise that ecological understanding serves as a scientific foundation for climate literacy. In this way, the study provides a more comprehensive perspective on preparing future teachers to address climate-related challenges through education.

The relevance of this study extends beyond educational outcomes and contributes to broader sustainability goals. By strengthening ecological understanding and climate literacy among future teachers, climate change education can support the achievement of Sustainable Development Goal (SDG) 4 on Quality Education, SDG 13 on Climate Action, and SDG 15 on Life on Land. Therefore, this study aims to examine the effectiveness of PjBL–STEM integration in improving ecological concept mastery and climate literacy among prospective primary school teachers and to contribute to the development of climate change education that supports sustainable development.

METHOD

Research Design

This study used a quasi-experimental research approach with a pretest–posttest control group design. This design aimed to examine the effect of integrating Project-Based Learning (PjBL) with a STEM approach on students' climate literacy and mastery of ecological concepts. In this design, two research groups, an experimental class and a control class, were given a pretest before the treatment and a posttest after the treatment. The experimental class participated in STEM-integrated PjBL, while the control class participated in conventional environmental education.

Research Population and Sample

This study was conducted at an Islamic higher education institution during the 2025/2026 academic year. The population comprised 144 fourth-semester students enrolled in the

Environmental Education course, distributed across four parallel classes. To ensure group equivalence, an independent-samples t-test was conducted using students' academic achievement data from the previous semester. The results indicated no significant difference between the selected classes ($t(70) = 0.84$, $p = .405$), suggesting comparable initial abilities. As this study employed a quasi-experimental design, random assignment was not feasible because the existing class structure was maintained. To minimise potential selection bias, two classes with equivalent academic backgrounds were selected. Following consultation with the course lecturer, Class IV D was assigned as the experimental group ($n = 36$) and Class IV A as the control group ($n = 36$), resulting in a total sample of 72 students.

Research Procedure

The intervention was conducted over four instructional meetings during the 2025/2026 academic year. Four meetings were considered sufficient because they represented one complete PjBL–STEM learning cycle, encompassing problem identification, investigation, solution design, project development, and presentation, in accordance with the learning outcomes of the Environmental Education course. Before implementation, lesson plans and student worksheets were developed to support climate change education and sustainability-oriented learning.

Before the intervention, both groups completed a pretest to assess their initial mastery of ecological concepts and climate literacy. The experimental group then participated in STEM-integrated Project-Based Learning (PjBL–STEM), which consisted of five stages: reflection, research, discovery, application, and communication. During the reflection stage, students identified local climate change issues and their impacts on environmental sustainability. In the research stage, students collected and analysed information from scientific articles, environmental reports, and digital resources. During the discovery and application stages, students designed project-based solutions, including climate action plans and environmental education programmes relevant to primary school contexts. The STEM components were integrated throughout the learning process through scientific investigation of climate-related phenomena (Science), the use of digital information sources and environmental data (Technology), the design of mitigation and adaptation solutions (Engineering), and the analysis and interpretation of environmental data (Mathematics). Finally, students presented and discussed their project outcomes during the communication stage. The control group received conventional Environmental Education instruction through lectures, discussions, and assignments. Following the intervention, both groups completed a posttest to measure improvements in ecological concept mastery and climate literacy. The data were analysed using the Kolmogorov–Smirnov test for normality, Levene's test for homogeneity of variance, independent-samples t-tests, N-gain analysis, and MANOVA.

The implementation of PjBL–STEM in this study followed the instructional framework proposed by Laboy-Rush (2011). As illustrated in Figure 1, the learning process consisted of five interconnected stages: reflection, research, discovery, application, and communication.

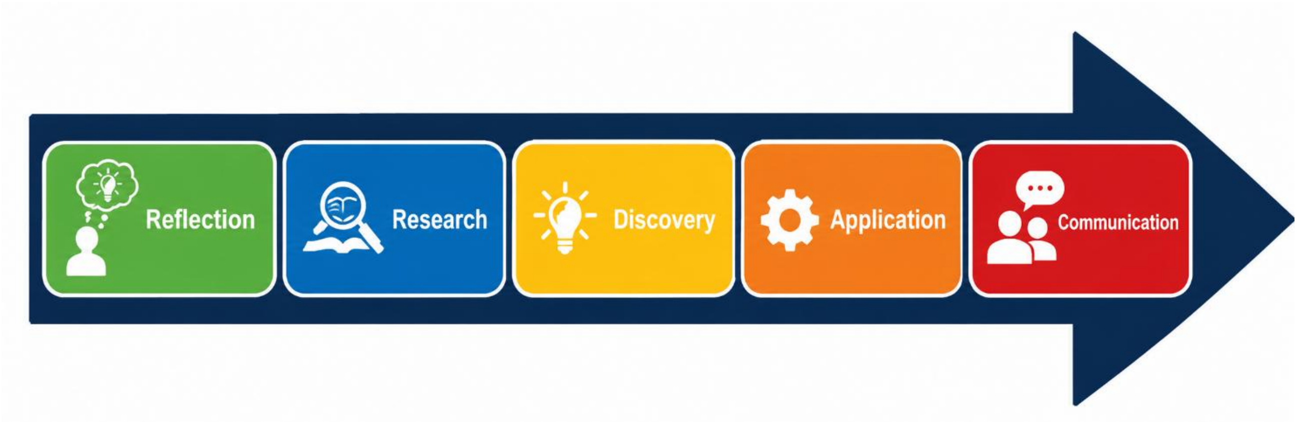

Figure 1. PJBL-STEM Syntax

PJBL–STEM learning consists of five stages designed to facilitate meaningful and effective learning (Laboy-Rush, 2011), namely reflection, research, discovery, application, and communication. The reflection stage provides a problem context that initiates the inquiry process. During the research stage, students gather and analyse information to strengthen their understanding of concepts relevant to the project. The discovery stage emphasises investigation, problem-solving, and collaboration in designing project solutions. The application stage focuses on implementing, testing, and refining the proposed solutions based on established criteria. Finally, in the communication stage, students present and discuss their project outcomes, thereby developing communication, collaboration, and reflective thinking skills through constructive feedback.

Research Instruments

The research instruments consisted of essay tests designed to assess students' mastery of ecological concepts and climate literacy. Ecological concept mastery was measured using indicators that covered organism–environment interactions, ecosystem balance and change, energy flow, biogeochemical cycles, and the impacts of human activities on ecological systems.

Climate literacy was operationalised as the cognitive dimension, including understanding of climate change concepts, causes, and mechanisms; environmental and societal impacts; climate data interpretation; and the formulation of mitigation and adaptation strategies aligned with the Sustainable Development Goals (SDGs). An essay-test format was selected because it enables students to demonstrate higher-order thinking skills, scientific reasoning, data interpretation, and problem-solving abilities related to climate change issues.

The instrument consisted of 10 essay items for ecological concept mastery and 10 essay items for climate literacy. Each item was scored on an analytical rubric ranging from 0 to 5, yielding a maximum score of 50 for each instrument. All items were developed based on the revised Bloom's Taxonomy, covering cognitive levels from understanding (C2) to creating (C6). Content and construct validity were evaluated by three experts in environmental education, science education, and educational assessment. The expert validation process yielded an average feasibility score of 79.18%, indicating that the instrument was suitable for use with minor revisions. Furthermore, empirical validity testing showed that all items met the validity criterion, with item–total correlation coefficients exceeding the minimum threshold ($r > 0.224$). Reliability testing using Cronbach's Alpha produced a coefficient of 0.949, indicating excellent internal consistency and confirming that the instrument was highly reliable.

Table 1. Instrument for Measuring Ecological Concept Mastery and Climate Literacy

No.	Variable	Indicator	Cognitive Level	Sample Question
1.	**Ecological Concept Mastery**	Interaction between organisms and the environment	C2	Explain the relationship between organisms and their environment within an ecosystem.
			C3	Analyze the relationship between biotic and abiotic components in an ecosystem.
		Ecosystem balance and change	C3	Explain changes in ecosystem balance caused by natural factors.
			C4	Analyze the impact of human activities on the balance of ecosystems.
		Energy flow in ecosystems	C2	Explain the flow of energy within an ecosystem.
			C3	Construct a food chain diagram that illustrates energy flow in an ecosystem.
		Matter cycles (water, carbon, nitrogen)	C2	Explain the main stages of one biogeochemical cycle.
			C4	Analyze the role of humans in influencing the carbon or nitrogen cycle.
		Impact of human activities on ecological systems	C4	Analyze cause–effect relationships between human activities and ecosystem changes.
			C5	Propose solutions to reduce the negative impacts of human activities on ecological systems.
2.			C1	Explain the definition of climate change.

No.	Variable	Indicator	Cognitive Level	Sample Question
	Climate Literacy	Basic concepts of climate change	C2	Distinguish between climate change and weather change.
		Causes and mechanisms of climate change	C2	Explain the factors that cause climate change.
			C3	Analyze the mechanism of the greenhouse effect.
		Impacts of climate change	C3	Explain the impacts of climate change on ecosystems.
			C4	Analyze the impacts of climate change on human life.
		Analysis of climate data and information	C4	Analyze climate data graphs or tables to explain climate change trends.
		Mitigation, adaptation, and links to the SDGs	C5	Evaluate climate change mitigation efforts that can be implemented in the surrounding environment.
			C6	Design a climate change adaptation program aligned with the SDGs for an elementary school context.

Data Analysis Techniques

The research data were analysed using statistical software. Descriptive statistics (mean and standard deviation) were used to describe students' ecological concept mastery and climate literacy. Before hypothesis testing, the data were examined for normality and homogeneity. Improvement in learning outcomes was measured using the normalized gain (N-gain) index and interpreted according to the criteria proposed by Hake (1999): high ($g \geq 0.70$), moderate ($0.30 \leq g < 0.70$), and low ($g < 0.30$). After the assumptions were met, hypothesis testing was conducted using independent-samples t-tests and Multivariate Analysis of Variance (MANOVA) at a significance level of $\alpha = 0.05$ to determine differences between the experimental and control groups (Ridwan & Lestari, 2025).

RESULTS AND DISCUSSION

Table 2 presents the descriptive statistics and assumption test results for ecological concept mastery and climate literacy in both the PjBL–STEM and control groups. The table includes mean scores, N-gain values, standard deviations, minimum and maximum scores, and the results of the normality and homogeneity tests.

Table 2. Descriptive Statistics and Assumption Test Results for Ecological Concept Mastery and Climate Literacy

Variable	Component	PjBL–STEM Class (Pretest)	PjBL–STEM Class (Posttest)	Control Class (Pretest)	Control Class (Posttest)
Ecological Concepts	N	36	36	36	36
	Mean	39.35	60.37	38.29	56.58
	N-gain	–	0.35 (Moderate)	–	0.29 (Low)

Variable	Component	PjBL–STEM Class (Pretest)	PjBL–STEM Class (Posttest)	Control Class (Pretest)	Control Class (Posttest)
	Standard Deviation	14.79	10.82	6.61	7.63
	Minimum Score	11.67	28.33	26.67	41.67
	Maximum Score	58.00	78.33	50.00	71.67
	Normality Test (K–S)	0.200	0.200	0.200	0.200
	Interpretation	Normal	Normal	Normal	Normal
	Homogeneity Test (Levene)	–	0.252	–	0.252
	Interpretation	–	Homogeneous	–	Homogeneous
Climate Literacy	N	36	36	36	36
	Mean	41.12	66.84	40.78	58.46
	N-gain	–	0.42 (Moderate)	–	0.31 (Moderate)
	Standard Deviation	13.96	11.24	12.87	10.91
	Minimum Score	13.33	33.33	16.67	36.67
	Maximum Score	60.00	83.33	58.33	73.33
	Normality Test (K–S)	0.200	0.200	0.200	0.200
	Interpretation	Normal	Normal	Normal	Normal
	Homogeneity Test (Levene)	–	0.281	–	0.281
	Interpretation	–	Homogeneous	–	Homogeneous

As shown in Table 2, both ecological concept mastery and climate literacy improved in the experimental and control groups. The results of the Kolmogorov–Smirnov test indicated that all datasets were normally distributed ($p = .200$). In contrast, Levene's test confirmed the homogeneity of variance for both variables ($p > .05$). These findings indicate that the assumptions for subsequent parametric analyses were satisfied. As shown in Table 2, both ecological concept mastery and climate literacy met the assumptions required for parametric analyses. The Kolmogorov–Smirnov test indicated that all datasets were normally distributed ($p > .200$). In contrast, Levene's test confirmed the homogeneity of variance for both variables ($p > .05$). Therefore, subsequent parametric analyses were conducted to compare learning outcomes between the experimental and control groups.

The results presented in Table 2 indicate that both ecological concept mastery and climate literacy improved in the experimental and control groups, with greater gains observed in the PjBL–STEM class. This finding suggests that integrating Project-Based Learning and STEM provides a more meaningful learning experience than conventional instruction. The improvement can be attributed to students' active involvement in investigating authentic climate change issues, analysing environmental problems, and developing project-based solutions. Through these activities, students were encouraged to connect theoretical ecological concepts with real-world environmental challenges, thereby facilitating deeper conceptual understanding and more meaningful learning. From a constructivist perspective, learning occurs when students actively construct knowledge through interaction with their environment and prior experiences. The PjBL–STEM approach supports this process by engaging students in inquiry, problem-solving, collaboration, and reflection throughout the learning cycle. Furthermore, the integration of Science, Technology, Engineering, and Mathematics enabled students to examine climate change from multiple perspectives, interpret environmental data, and design evidence-based solutions. These experiences not only strengthened mastery of ecological concepts but also enhanced climate literacy by developing students' ability to understand climate issues, evaluate information, and formulate mitigation and adaptation strategies. The findings are consistent with previous studies reporting that STEM-based learning and Project-Based Learning can improve conceptual understanding, critical thinking, and environmental literacy through authentic and interdisciplinary learning experiences (Bashirun et al., 2023; Botella et al., 2022).

Trott & Weinberg (2020) emphasised that climate change education is more effective when students engage directly with real-world environmental issues and participate in solution-oriented activities. Therefore, the higher gains achieved by the PjBL–STEM group suggest that integrating project-based inquiry with STEM principles provides an effective framework for developing both ecological understanding and climate literacy among prospective primary school teachers.

Table 3 presents the results of the independent-samples t-test comparing ecological concept mastery and climate literacy between the PjBL–STEM and control groups. The analysis includes the t-statistic, degrees of freedom, significance values, and effect sizes (Cohen's d).

Table 3. Independent-Samples t-Test Results for Ecological Concept Mastery and Climate Literacy

Variable	Group	N	Mean (M)	SD	t	df	p
Ecological Concept Mastery	PjBL–STEM	36	60.37	10.82	3.72	70	.000
	Control	36	56.58	7.63			
Climate Literacy	PjBL–STEM	36	66.84	11.24	3.21	70	.002
	Control	36	58.46	10.91			

As presented in Table 3, the independent-samples t-test revealed significant differences between the PjBL–STEM and control groups in both ecological concept mastery and climate literacy ($p < .05$). Students in the PjBL–STEM group obtained significantly higher mean scores than those in the control group. The effect size analysis further indicated meaningful educational effects, with Cohen's d values of 0.45 for ecological concept mastery and 0.72 for climate literacy. These findings demonstrate that the PjBL–STEM approach contributed positively to improving both learning outcomes compared with conventional instruction.

The significant improvement in ecological concept mastery and climate literacy observed in the PjBL–STEM group may be attributed to the active, authentic learning experiences embedded in the instructional approach. Unlike conventional learning, which often emphasises the transmission of information, PjBL–STEM engages students in investigating real-world climate change issues, analysing environmental data, and developing project-based solutions. These activities require students to apply ecological concepts in meaningful contexts, thereby facilitating deeper conceptual understanding and promoting the transfer of knowledge to real-life situations. From a constructivist perspective, learning occurs when students actively construct knowledge through interaction with their environment and prior experiences. The PjBL–STEM framework supports this process by encouraging inquiry, collaboration, problem-solving, and reflection throughout the learning cycle. During the reflection and research stages, students explored authentic environmental problems and gathered relevant information from various sources. The discovery and application stages enabled them to connect theoretical ecological concepts with practical solutions, while the communication stage provided opportunities to articulate and defend their ideas. These processes are likely to have contributed to the higher ecological concept mastery achieved by students in the experimental group.

The interdisciplinary nature of STEM education can also explain the improvement in climate literacy. Climate literacy requires more than factual knowledge; it involves the ability to interpret information, evaluate evidence, understand complex environmental systems, and formulate appropriate mitigation and adaptation strategies. Through the integration of Science, Technology, Engineering, and Mathematics, students were encouraged to analyse climate-related phenomena from multiple perspectives, utilise digital resources, interpret environmental data, and design evidence-based solutions. Such learning experiences help students develop a more comprehensive understanding of climate change and strengthen their capacity to make informed environmental decisions.

These findings are consistent with previous studies demonstrating that Project-Based Learning and STEM-based instruction enhance conceptual understanding, critical thinking, scientific literacy, and environmental awareness through authentic, problem-oriented learning experiences (Kazazoglu, 2025; Shutaleva & Nikonova, 2020). The results also support the argument of Trott & Weinberg (2020), who emphasised that climate change education becomes more effective when learners engage directly with real environmental issues and participate in solution-oriented activities. The findings extend previous research by showing that ecological concept mastery and climate literacy can be developed simultaneously through an integrated PjBL–STEM approach. This supports the theoretical proposition that ecological understanding provides an important scientific foundation for climate literacy, enabling future teachers to understand better, communicate, and respond to climate-related challenges in ways that support the achievement of the Sustainable Development Goals (SDGs).

Table 4 presents the results of the Multivariate Analysis of Variance (MANOVA) examining the overall effect of the learning model on ecological concept mastery and climate literacy. The analysis was conducted to determine whether significant differences existed between students who participated in the PjBL–STEM intervention and those who received conventional instruction.

Table 4. Results of the MANOVA on the Mastery of Ecological Concepts and Climate Literacy

Multivariate Statistic	Value	F	df	Sig.	Partial η^2
Wilks' Lambda	0.688	15.42	(2, 69)	< 0.001	0.312

Notes:
Dependent variables: mastery of ecological concepts and climate literacy.
Factor: learning model (PjBL–STEM and conventional).

As presented in Table 4, the MANOVA results revealed a statistically significant multivariate effect of the learning model on the combined dependent variables, namely ecological concept mastery and climate literacy (Wilks' Λ = 0.688, $F(2, 69) = 15.42$, $p < .001$, partial $\eta^2 = .312$). This result indicates that the type of learning model significantly influenced students' overall learning outcomes. The partial η^2 value of .312 suggests that approximately 31.2% of the variance in the combined dependent variables was explained by the learning model, indicating a substantial multivariate effect. The MANOVA results reflect the combined effect on both dependent variables and do not indicate whether the effect was greater for ecological concept mastery or climate literacy. Therefore, follow-up univariate analyses (Tests of Between-Subjects Effects) were conducted to examine the individual contribution of the learning model to each dependent variable. The MANOVA test results showed that the learning model had a significant simultaneous effect on students' mastery of ecological concepts and climate literacy (Wilks' Λ = 0.688; $F(2,69) = 15.42$; $p < 0.001$). The partial eta squared value of 0.312 indicated a large effect size, indicating that integrating Project-Based Learning with the STEM approach had a strong, integrated impact on both dependent variables. These results strengthen the findings of the independent-samples t-test, which showed that the increase in learning outcomes in the PjBL–STEM class was consistently higher than in the control class.

The results of this study indicate that implementing STEM-integrated Project-Based Learning (PjBL–STEM) had a significant and meaningful impact on students' ecological concept mastery and climate literacy. This finding is reflected in the higher posttest scores, N-gain values, and effect sizes observed in the PjBL–STEM group compared with the control group. Furthermore, the MANOVA results revealed a statistically significant multivariate effect of the learning model on the combined dependent variables, indicating that PjBL–STEM simultaneously influenced both ecological concept mastery and climate literacy. The significant multivariate effect suggests that integrating Project-Based Learning and STEM provides a comprehensive learning environment that supports the concurrent development of multiple learning outcomes. Through engagement in authentic climate change investigations, environmental data analysis, collaborative problem-solving, and project development, students were encouraged to apply ecological knowledge in meaningful contexts while simultaneously developing their understanding of climate-related issues. These findings support the view that interdisciplinary and project-based learning experiences can effectively promote both conceptual understanding and climate literacy among prospective primary school teachers. The findings are consistent with constructivist learning theory, which emphasises that knowledge is actively constructed through meaningful experiences and social interaction. They also align with previous studies reporting that STEM-based and project-based learning approaches enhance conceptual understanding, critical thinking, scientific literacy, and environmental awareness through authentic and inquiry-oriented learning experiences (Giac et al., 2025; Trott & Weinberg, 2020). Therefore, the present study provides empirical evidence that PjBL–STEM is an effective instructional approach for improving both ecological concept mastery and climate literacy in the context of climate change education and sustainable development.

The improvement in ecological concept mastery among students in the PjBL–STEM group suggests that this approach can address one of the major challenges in ecological learning, namely the tendency for ecological concepts to be taught in abstract, fragmented, and decontextualised ways. Through project-based investigations of climate change issues, students were required to actively construct knowledge by connecting ecological concepts with authentic environmental problems. This process reflects the principles of constructivist learning theory, which emphasises that meaningful understanding is developed through active engagement, inquiry, and reflection. Rather than memorising isolated concepts, students explored ecological relationships, analysed environmental evidence, and applied their understanding to real-world situations, thereby promoting deeper conceptual learning.

The positive outcomes may also be explained by the inquiry-based and collaborative nature of the PjBL–STEM approach. During project activities, students worked collaboratively to identify problems, collect and interpret information, evaluate alternative solutions, and communicate their findings. Such learning experiences encouraged scientific inquiry, critical thinking, and the construction of shared knowledge. Through collaboration and discussion, students were exposed to multiple perspectives, enabling them to refine their understanding of ecological systems and climate-related issues. These findings support previous studies indicating that STEM-integrated project-based learning enhances conceptual understanding and higher-order thinking skills through authentic and problem-oriented learning experiences (Kazazoglu, 2025; Shutaleva & Nikonova, 2020). The findings also demonstrate that PjBL–STEM effectively promoted climate literacy. Climate literacy requires learners not only to understand climate change concepts but also to interpret information, evaluate evidence, and formulate appropriate mitigation and adaptation strategies. The interdisciplinary integration of Science, Technology, Engineering, and Mathematics provided students with opportunities to analyse climate-related data, investigate environmental phenomena, and develop evidence-based solutions. Consequently, students gained a more comprehensive understanding of climate change and its implications for environmental sustainability. The MANOVA results revealed that the learning model had a significant multivariate effect on the combined outcomes of ecological concept mastery and climate literacy. This finding indicates that PjBL–STEM simultaneously contributed to improvements in both competencies. Consistent with previous studies (Giac et al., 2025; Trott & Weinberg, 2020). The results suggest that authentic, interdisciplinary, and project-based learning experiences provide an effective framework for preparing prospective teachers to understand and address complex environmental challenges. Therefore, PjBL–STEM can be considered a promising approach for climate change education and for supporting the achievement of the Sustainable Development Goals (SDGs).

From a theoretical perspective, the findings of this study support the view that meaningful learning occurs when students actively explore real-world problems rather than merely receiving information from lecturers. In the PjBL–STEM class, students were not only introduced to concepts related to ecology and climate change. They were also challenged to investigate environmental issues, analyse relevant information, and propose practical solutions. These learning experiences enabled students to connect theoretical knowledge with real situations, making ecological concepts more understandable and relevant. The improvement in students' ecological concept mastery can be explained by the nature of the project activities, which required them to examine climate change issues from multiple ecological perspectives. Through observation, discussion, information gathering, and problem-solving activities, students gradually developed a deeper understanding of ecosystem interactions, environmental change, and the consequences of human activities. Rather than learning concepts in isolation, students were encouraged to view ecological phenomena as interconnected systems, thereby strengthening their conceptual understanding.

The learning process also reflected the stages of experiential learning. Students began by engaging with authentic environmental problems encountered in everyday life. They then reflected on these issues through discussion and analysis, connected their observations with ecological concepts and climate change theories, and finally applied their understanding by developing and presenting project-based solutions. This sequence of experience, reflection, conceptual understanding, and application provided opportunities for students to learn actively and meaningfully. Similarly, the improvement in climate literacy may be attributed to the interdisciplinary nature of the PjBL–STEM approach. Throughout the project activities, students analysed climate-related information, interpreted environmental data, evaluated potential solutions, and discussed mitigation and adaptation strategies. These activities helped students move beyond simply understanding climate change as a scientific concept and encouraged them to think critically about its implications and possible responses.

These findings are consistent with previous studies suggesting that project-based and STEM-oriented learning can improve students' conceptual understanding, critical thinking, and environmental awareness by providing authentic and problem-centred learning experiences (Kazazoglu, 2025; Shutaleva & Nikonova, 2020). Therefore, the present study suggests that PjBL–STEM offers a valuable learning environment for developing both ecological concept mastery and climate literacy among prospective elementary school teachers.

Conversely, the relatively lower results in the control class underscore the limitations of conventional learning in simultaneously developing complex competencies such as mastery of ecological concepts and climate literacy. Learning that focuses on lectures and memorization may still improve declarative knowledge but is less effective at building interconnectedness among concepts and application skills. These findings emphasize that climate change education that is not designed contextually and participatory risks producing partial and unsustainable understanding (Lestari & Rahmawati, 2020; Sumarni & Kadarwati, 2020; Terzieva et al., 2025).

Implicationally, the results of this study position PjBL–STEM as a potential, but not yet final, approach to climate change education. The integration of PjBL–STEM has proven effective in simultaneously building ecological competencies and climate literacy. Still, its implementation needs to be refined so that mastery of ecological concepts can develop in tandem with climate literacy in a balanced manner. For the education of prospective elementary school teachers, these findings underscore the importance of designing learning that is not only engaging and contextual but also conceptually robust, so that prospective teachers can transform this understanding into sustainable learning practices. Thus, PjBL–STEM can contribute more optimally to the achievement of the Sustainable Development Goals (SDGs), particularly SDG 4 and SDG 13, through education that is not only transformative, but also reflective and critical (Echavez et al., 2024; Giac et al., 2025; Rochintaniawati et al., 2025).

CONCLUSION

This study concludes that integrating Project-Based Learning with a STEM approach (PjBL–STEM) effectively improves students' mastery of ecological concepts and climate literacy, aligning with the stated research objectives. Empirical findings indicate significant differences between PjBL–STEM classes and conventional classes, both univariate and multivariate, confirming that PjBL–STEM provides a more meaningful learning experience than conventional learning. Through active engagement in contextual, problem-based projects, students not only experience improved cognitive outcomes but also develop a more systemic and reflective mindset regarding environmental issues and climate change. The implications of these findings suggest that PjBL–STEM is a relevant and strategic learning approach for climate change education, particularly for preparing prospective elementary school teachers with a strong ecological understanding and practical climate literacy. Therefore, it is recommended that PjBL–STEM be more broadly integrated into teacher education curricula, particularly in courses related to environmental and sustainability education. Further research is recommended to examine the long-term impact of PjBL–STEM implementation on students' attitudes, behaviors, and pedagogical practices, and to explore its integration with digital learning platforms to strengthen its contribution to transformative education aligned with the achievement of the Sustainable Development Goals (SDGs).

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