



Carbon Emission Project through Deep Learning: A Strategy for Developing Students' Competencies and Environmental Care Attitude

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Abstract: Climate change education is a national priority due to escalating global warming impacts and students' low competencies and environmental awareness. This study aims to examine the effectiveness of a project-based deep learning approach through the Deep Learning–Carbon Emission Project (DL-CEP) in improving both student competencies and environmental care attitudes. A mixed-methods design with a one-group pretest–posttest approach was conducted involving 36 tenth-grade science students (aged 15–16) at SMA Juara Wirautama, Indonesia. Instruments included competency tests, environmental attitude questionnaires, project rubrics, observations, and teacher interviews. Quantitative data were analysed using paired t-tests and Wilcoxon tests, while qualitative data were analysed thematically. Results showed significant improvements in competencies (65.07 to 89.93; $p < 0.05$; effect size = 0.84) and environmental care attitudes (66 to 79; $p < 0.05$; Cohen's $d = 1.56$). The novelty of this study lies in integrating deep learning, carbon emission analysis, and interdisciplinary science learning within a single project-based framework that simultaneously measures cognitive and affective outcomes using digital tools. However, the absence of a control group limits causal generalisation. Practically, DL-CEP can be adapted in other schools to support 21st-century skills and sustainable behaviour through contextual, technology-enhanced learning.

Keywords: Carbon emissions project; Climate change education; Deep learning; environmental care attitude; Student competence.

Introduction

Climate change has emerged as one of the most critical global challenges of the 21st century, threatening environmental sustainability, economic stability, and human well-being across the globe (Jayadi et al., 2023; Nazmi et al., 2023). As a maritime archipelago, Indonesia is particularly vulnerable to climate change impacts, including rising sea levels, extreme weather events, and ecological degradation (Fahri, Yuliantri, et al., 2023; Jayadiputra et al., 2020; Prihantini & Khoirunnisa, 2023). This vulnerability extends beyond geography into socio-economic dimensions, as a significant proportion of the population depends directly on climate-sensitive natural resources for their livelihoods (Fahri,

Kumalasari, et al., 2023; Kurniawati et al., 2024). Consequently, strengthening public understanding and adaptive capacity toward climate change has become an urgent national and global priority (Jayadiputra et al., 2020; Susanti et al., 2023). Education plays a fundamental role in addressing this crisis by equipping individuals with the knowledge, skills, and values necessary to respond to environmental challenges (Jayadi et al., 2023; Nazmi et al., 2023; Nugraha & Budimansyah, 2022). Climate change education (CCE) is increasingly recognised as essential for sustainable development and 21st-century competencies, particularly in fostering critical thinking, problem-solving, and responsible decision-making (Jayadi et al., 2023; Rosa & Nawawi, 2023; Tang, 2024). Climate change

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education is one of the three priority issues in Indonesia's national curriculum. Its primary objective is to develop awareness and enhance society's capacity to respond to climate crises in relevant and effective ways. The ability to respond to climate challenges is recognised as a key 21st-century competency. It is an integral part of national education goals that emphasise the development of resilient, adaptive citizens grounded in Pancasila values (Kemristek, 2024). Structured climate change education in schools not only broadens students' knowledge of the causes and impacts of climate change but also cultivates critical skills necessary for evaluating information, solving problems, and making sustainable decisions.

The Ministry of Research and Technology of the Republic of Indonesia has reaffirmed climate change education as a national curriculum priority to strengthen public awareness and adaptive capacity in addressing climate crises (Laily et al., 2023). Integrating climate issues into the curriculum enables students to understand the drivers and consequences of climate change while training them to make sustainability-oriented decisions (Feriyanto & Anjariyah, 2024). The competence to respond to climate change is also a fundamental aspect of 21st-century skills, emphasising readiness to address complex, dynamic global challenges (Wiandani, 2025). Consequently, climate change education should not be limited to theoretical knowledge; it should be oriented toward real-world applications.

Climate education is closely linked to environmental education, which extends beyond conceptual understanding to include environmental awareness and responsibility. As stated Umam et al. (2025), education should foster not only knowledge of environmental preservation but also a conscious commitment to protecting the environment. Awareness of pollution and carbon emissions encourages individuals to adopt simple yet meaningful pro-environmental behaviours, such as conserving electricity and reducing plastic waste.

Traditional teacher-centred learning models have notable limitations, particularly in providing students with opportunities to develop essential digital-era skills. One major drawback is the lack of interaction and collaboration, which are crucial for developing communication and teamwork skills (Aprianto et al., 2020). In response, the integration of technology and innovative pedagogical approaches has been promoted to create more participatory and collaborative learning environments. The deep learning model, as articulated by the current Minister of Education, Abdul Mu'ti, emphasises mindful, meaningful, and joyful learning experiences, enabling students to deeply understand and internalise learning content rather than merely

memorising it (R. Putri, 2024). Enhancing critical thinking skills is a valuable learning asset in the twenty-first century, and utilizing an educational framework that promotes this development can aid students' growth (Mutiarra et al., 2024; D. K. Putri et al., 2023).

Deep learning in education is a learning process that encourages students to fully comprehend and reflect on what they learn (Raup, 2022). Grounded in constructivist theory, deep learning emphasises active student engagement, critical inquiry, and reflective thinking. Knowledge is constructed through active learning experiences, social interaction, and reflection, enabling students to develop broader, more critical perspectives.

Technology-based learning aligns strongly with the deep learning approach. According to Raup et al. (2022), deep learning supports data-driven and contextual learning. In climate education, particularly on carbon emissions, technological tools such as carbon footprint calculators (e.g., *Jejak Karbonku* app) allow students to analyse and understand the environmental impacts of their daily activities in an interactive, contextual way.

Carbon footprint refers to the total greenhouse gas emissions generated by individual or institutional activities, expressed in carbon dioxide equivalents (CO₂) (Dirga et al., 2024). Higher consumption levels result in greater environmental impacts, contributing to global warming, air pollution, and climate-related disasters (Dirga et al., 2024). Implementing carbon footprint projects enables students to quantify emissions, identify their sources, and plan strategies to reduce them through behavioural changes and transitions to renewable energy sources such as solar and wind power.

This study introduces the Deep Learning-Carbon Emission Project (DL-CEP), which integrates carbon footprint analysis with household waste management initiatives, such as converting used cooking oil into reusable products. The DL-CEP model extends beyond classroom learning by incorporating outdoor learning activities and expert discussions with environmental and chemistry specialists. The project aligns with interdisciplinary science curricula under Indonesia's Merdeka Curriculum, integrating green chemistry, measurement, and alternative energy concepts in physics, and global warming topics in biology to foster critical thinking skills. Building on prior research by Putri (2024), this present study, which demonstrated the positive impact of deep learning on students' critical thinking and engagement, addresses a research gap by empirically examining the influence of DL-CEP on students' competencies and environmental care attitudes through technology-supported learning.

Student competencies refer to the skills required for effective learning and real-life problem-solving, including critical thinking, collaboration, problem-

solving, and responsible technology use commonly referred to as 21st-century skills (Trilling & Fadel, 2009). Learning models that are student-centred, collaborative, contextual, and community-integrated are essential for nurturing these competencies (Zubaidah, 2020). According to Asih & Halisiana (2022), students learn more effectively when they are facilitated through enjoyable activities in which they feel free to express their opinions. In addition, students are given space to think, reflect, and support one another throughout the learning process. This is in line with the expectation that DL-CEP learning can support students in expressing themselves, particularly in relation to mitigating the impacts of global warming.

Environmental care attitudes encompass awareness, responsibility, and pro-environmental behaviour developed through learning experiences (Warni & Wulandari, 2022; Wisman & Santoso, 2024). Prior studies have demonstrated significant relationships among students' environmental knowledge, attitudes, and behaviour (Arlistiani & Surbakti, 2020; Hakim, 2020).

Despite extensive research on environmental education, no previous study has comprehensively examined a deep learning-based carbon emission project that simultaneously measures its effects on student competencies and environmental care attitudes through digital technology. Thus, this study offers novelty by proposing the Deep Learning–Carbon Emission Project (DL-CEP) as an interdisciplinary cocurricular model integrating cognitive and affective domains within a technology-supported learning environment.

Despite the growing emphasis on climate change education (CCE), significant challenges persist. Previous studies highlight a discrepancy between climate change policy and its implementation in education, characterised by the marginalisation of CCE and limited collaboration among stakeholders (Jayadi et al., 2023). Traditional teacher-centred approaches remain dominant, limiting opportunities for meaningful and contextual learning experience (Ramdani et al., 2019; Ridho et al., 2020).

Furthermore, although digital technology is increasingly integrated into education, its use often remains confined to content delivery rather than facilitating deep and reflective learning processes (Tang, 2024; Zawacki-Richter et al., 2019). This limitation reduces opportunities for students to develop higher-order thinking skills such as critical thinking and problem-solving (Akbar et al., 2024; Mutiara et al., 2024; D. K. Putri et al., 2023).

Previous studies on environmental and climate education have generally focused on either cognitive outcomes or environmental attitudes separately, with

limited research integrating both aspects within a single interdisciplinary learning model supported by digital technology (Nazmi et al., 2023; Rosa & Nawawi, 2023). In addition, the lack of project-based and inquiry-oriented learning approaches further limits students' active engagement and their ability to connect scientific concepts with real-world environmental issues (Bell, 2010; Fatmawati et al., 2021; Prabasari et al., 2021; Rahmadita et al., 2021)

Accordingly, this study addresses the following research questions: (1) How does project-based deep learning on carbon emission topics affect student competencies? (2) How does it influence students' environmental care attitudes? (3) How does the implementation of DL-CEP enhance both competencies and environmental attitudes throughout the learning process?

The significance of this study lies in its contribution to educational theory and practice, particularly in advancing deep learning pedagogy, supporting interdisciplinary science instruction, and fostering environmentally responsible future citizens equipped with essential 21st-century skills.

Method

Research Design

This study employed a mixed-methods approach with a sequential explanatory design, in which quantitative data were collected and analysed first, followed by qualitative data to interpret the quantitative findings further (Creswell & Creswell, 2018). This design was selected to examine the effectiveness of the *Deep Learning–Carbon Emission Project* (DL-CEP) not only in terms of statistical outcomes but also in relation to students' learning processes, contextual experiences and applied project based learning. These create barriers to students' self-efficacy and critical thinking skills (Damayanti et al., 2022; Qurniati & Wahyudiati, 2023; Tosun & Taşkesenligil, 2013; Wahyudiati & Qurniati, 2022). The quantitative phase used a pre-experimental one-group pretest–posttest design to measure changes in student competencies and environmental care attitudes. The qualitative phase served as complementary data to explain and strengthen the interpretation of the quantitative results.

Research Context and Participants

The study was conducted at SMA Juara Wirautama, Indramayu, Indonesia, during the first semester of the 2025/2026 academic year (August–October 2025) over five instructional sessions. The school was selected due to adequate science laboratory and computer facilities, and institutional support for deep learning and contextual environmental projects.

The quantitative participants consisted of 36 tenth-grade students (Phase E), selected through purposive sampling based on their relevance to global warming and carbon emissions. All students participated fully in the learning activities and data collection. Qualitative participants included three science teachers (Biology, Chemistry, and Physics), purposively selected from a population of 15 teachers to serve as observers and informants.

Variables and Intervention

The independent variable was deep learning-based carbon emission learning (DL-CEP), integrating mindful, meaningful, and joyful learning principles, the use of the *Jejak Karbon* app, a household waste oil-to-soap project, and interdisciplinary collaboration through environmental action activities. The dependent variables were student competencies and environmental care attitudes.

Data Collection and Instruments

Quantitative data were collected using a student competency test and an environmental care attitude questionnaire administered at the pretest and posttest stages. The questionnaire employed a four-point Likert scale, and students' project performance was assessed using a standardised project rubric. Quantitative instruments were validated through content validity and reliability testing and adapted from previous environmental education studies within the Merdeka Curriculum framework (Sugiyono, 2023).

Qualitative data were collected through semi-structured interviews with science teachers, direct classroom and project observations, and document analysis, including photographs, project reports, and student products. Qualitative data collection followed descriptive, focused, and selective stages (Sugiyono, 2023).

Data Analysis

Quantitative data were analysed using descriptive and inferential statistics. Normality testing guided the selection of hypothesis-testing procedures. Differences between pretest and posttest scores were analysed using paired sample *t*-tests or Wilcoxon signed-rank tests when data were not normally distributed. The magnitude of the intervention effect was calculated using effect size (Cohen, 1988).

Qualitative data were analysed using Miles and Huberman's interactive model, comprising data reduction, data display, and conclusion drawing. Data credibility was ensured through source and method triangulation. Qualitative findings were used to reinforce and explain quantitative results, particularly regarding the emergence of mindful, meaningful, and

joyful learning processes during DL-CEP implementation.

Result and Discussion

The DL-CEP learning process began with an apperception activity focusing on the issue of accumulated waste and the lack of public awareness regarding waste segregation at home, school, and in the surrounding community. This initial activity was conducted alongside a pretest to assess students' baseline competencies. These conditions were identified as the core problems in science learning, particularly within the topic of global warming, which intersects concepts from Physics, Chemistry, and Biology.



Figure 1. Initial competency assessment followed by carbon footprint completion

The first learning activity, as illustrated in the figure, involved calculating carbon emissions using the *jejakkarbonku.id* carbon footprint calculator. This platform is officially released under an open-access license with no copyright restrictions by the Institute for Essential Services Reform (IESR).



Figure 2. Utilisation of digital technology for carbon footprint calculation

As a conceptual trigger, the teacher posed reflective questions to students, such as whether they had replaced

single-use plastic bottles with reusable tumblers, reduced the use of private vehicles, and understood the relationship between waste generation and carbon emissions. At this stage, *meaningful learning* emerged as students began engaging in group discussions that explored both supportive and opposing perspectives on daily practices contributing to carbon emissions.

Table 1. Pretest and Posttest Results of Student Competencies

Category	Score	Range Pretest	Percentage	Range Posttest	Percentage
Not Achieved	<71	22	61	0	0
Beginning to Achieve	71-79	8	22	3	8
Achieved	80-89	5	14	11	31
Highly Achieved	90-100	1	3	22	61

The distribution of minimum, mean, and maximum scores further illustrates a substantial improvement in student competencies following the implementation of the DL-CEP learning model.

Table 2. Analysis of Students' Competencies Results

Data Distribution	Pretest	Posttest	Difference
Max	92.50	100.00	
Min	37.50	75.00	
Mean	65.07	89.93	24.86
Sd Deviation	13.19	7.29	5.89

The comparison of students' competencies scores between the pretest and posttest is illustrated in the Figure 3.

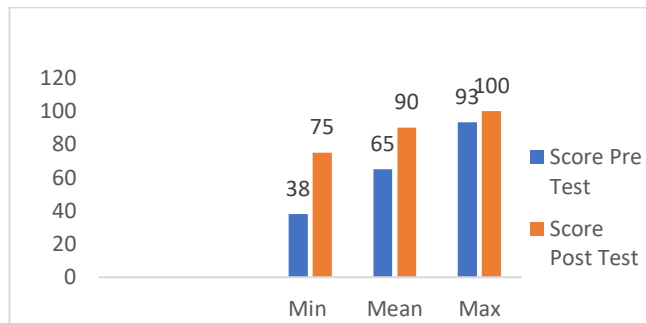


Figure 3. Students' Competence Score Graph

The data from the normality tests of students' skills before and after the implementation of the learning were analysed using two tests: the Kolmogorov-Smirnov and Shapiro-Wilk tests, as presented below.

Table 3. Normality Test of Students' Competencies Data

Data	Kolmogorov-Smirnov ^a			Shapiro-Wilk		
	Statistic	Df	Sig.	Statistic	Df	Sig.
Pretest	0.16	36	0.02	0.97	36	0.41
Posttest	0.18	36	0.005	0.92	36	0.01

Statistical Analysis of the Effect of Learning on Student Competencies

The distribution of students' competency scores in the pretest and posttest phases is presented in Table 4.1. Based on score ranges, the distribution of student competencies is described as follows:

There was a highly significant increase in the mean scores from pretest to posttest. The average score increased from 65.07 to 89.93, a gain of 24.86 points. The Shapiro-Wilk normality test indicated that the initial competencies test data (pretest) were normally distributed, with a p-value of 0.41 ($p > 0.05$). In contrast, the normality test results for the final skill test data (posttest) revealed a p-value of 0.009 ($p < 0.05$), indicating that the data were not normally distributed.

Since the pretest and posttest data were not normally distributed, the relationship between the initial and final competency test scores could not be analysed using the Paired-Samples t-test. Therefore, the significance test was conducted using the Wilcoxon signed-rank test.

Table 4. Wilcoxon Test of the Effect on Students' Competencies Data

Pretest - Posttest Data	N	Mean Rank	Sum of Ranks
Negative Ranks	0 ^a	0.00	0,00
Positive Ranks	33 ^b	17.00	561.00
Ties	3 ^c		
Total	36		
Pretest - Posttest			
Z	-5.01 ^b		
Asymp. Sig. (2-tailed)	0.00		

Note;

- a. Negative Rank, which means Posttest score < Pretest
- b. Positive Ranks, which means Posttest score > Pretest
- c. Ties, which means Posttest score = Pretest

Table 5. Effect Size Analysis of DL-CEP Learning on Students' Competences

Statistic	Value
Z	-5.01
N	36
R	0.84
Category	Very Large Effect

was $p=0.00$ ($p<0.05$), confirming a statistically significant difference between pretest and posttest scores.

The 95% confidence interval ranged from -15.444 to -9.94 , with all values falling below zero, suggesting that the observed improvement was consistent across participants and unlikely to have occurred by chance. To further assess the magnitude of this effect, an effect size analysis using Cohen's d was performed. The resulting value ($d = 1.56$) falls within the very large effect category according to Cohen's criteria. The 95% confidence interval for Cohen's d (-2.05 to -1.07) further supports the robustness and consistency of the observed effect.

These findings indicate that the deep learning approach had a substantial and meaningful influence on changes in students' environmental care attitudes.

Descriptive Trends in Students' Scientific Skills and Attitudes

In addition to inferential analysis, descriptive data revealed notable improvements in students' scientific skills and attitudes toward environmental care. The average scientific skill score increased from 65 in the pretest to 90 in the posttest. The proportion of students classified in the high-skill category rose from 3% at pretest to 31% at posttest, while the proportion of students with low or insufficient skill levels decreased from 61% to 0%.

Similarly, questionnaire data showed an increase in the average environmental care attitude score from 66 to 79. At the pretest stage, 64% of students had not yet met the expected level of environmental care attitudes; this proportion decreased to 19% after the intervention. Conversely, the category of students demonstrating very high environmental care attitudes, which was absent at pretest, increased to 11% at posttest. Taken together, these patterns support rejecting the null hypothesis (H_0) and accepting the alternative hypothesis (H_1), indicating that the implemented learning approach effectively enhanced both scientific skills and attitudes toward environmental care.

This section presents a qualitative analysis of the effectiveness of deep learning in fostering students' scientific skills, environmental care attitudes, and joyful emotional engagement during carbon-emission learning activities. Data were obtained through interviews, classroom observations, and project documentation.

a. Interview Findings

Reflection activities were conducted to evaluate the achievement of research objectives and to provide feedback for instructional improvement. Classroom observations focused on students' engagement during learning activities and the quality of student-produced projects, informing teacher reflection and refining future instructional planning. I, a science teacher and

laboratory coordinator, explained her observations and evaluations, which stated:

"Regarding the outcomes that emerged after the carbon emission learning activities, they were really impressive, because students became more skilful through hands-on practice, and the results can serve as good portfolios by directly sharpening their skills. In my view, through the DL-CEP learning activities, students can practice directly by producing tangible, useful products (such as processing used cooking oil into soap), while simultaneously developing problem-solving skills to address waste-related issues. In terms of attitudes, students also showed increased self-confidence and became more sensitive to their surroundings, for example, by turning off air conditioners and lights when they are not in use." (I/G/20112025)

In line with this, L, a Biology teacher, also emphasised the importance of comprehensive competency assessment in interdisciplinary cocurricular project-based learning and stated:

"Deep learning is learning that is in-depth, meaning that it is not limited to theory alone. When there is a problem, answering questions is not enough; students must also provide solutions. Therefore, classroom projects in DL-CEP learning are intended to enable students to develop solutions to real-life problems. For example, when students face problems related to accumulated household waste, projects are designed to address how to overcome waste issues. Ideally, learning should be like this – it should foster greater sensitivity. Sensitivity does not emerge spontaneously in students but can be cultivated, for example, through deep learning. When connected to the project examples mentioned earlier, students become more aware of the availability of clean water, use water more efficiently, close water taps when they see them left open, and use water only as needed." (L/G/25112025)

Similarly, W, a Physics teacher, also highlighted the importance of comprehensive competency assessment in interdisciplinary cocurricular project-based learning and stated:

"Our observations show that DL-CEP learning is very in-depth because there are rewards and punishments applied after the completion of the project. As a result, students are expected to become more aware of the importance of environmental conservation, such as planting trees to prevent erosion in sensitive areas. The expected learning outcomes are truly positive; we observed that students were enthusiastic, skilled in practical activities such as pouring, measuring, and processing waste, and concerned about the environment. Most importantly, this interdisciplinary project makes learning time more efficient across Physics, Chemistry, and Biology within the overlapping topic of global warming, and it serves as a strong collaborative project that can be proposed as a cocurricular theme." (W/G/14122025)

These findings indicate that carbon-emission learning was implemented effectively, as reflected in interviews with three science teachers at the research site, all of whom expressed positive views of the deep learning approach. Their appreciation of project-based learning emphasised the overall positive learning outcomes, which were perceived as both meaningful and mindful.

Although developing environmental care attitudes requires sustained habituation, observable changes were evident in students' daily behaviours. Students were more inclined to turn off water taps properly, switch off air conditioners and lights when not in use, and demonstrate greater environmental awareness without external pressure. The learning process was carried out through a variety of engaging projects and activities that enabled students to demonstrate their competencies in tangible ways. These included laboratory activity reports, demonstrations of scientific attitudes during investigations of household carbon footprints, and observations of students' behaviours and performance during learning activities.

This research approach allowed teachers to capture students' development more holistically, rather than relying solely on written test scores. In addition, the integrated project-based design supported more efficient instructional time management, as a single project simultaneously addressed learning objectives across three subjects: Physics, Green Chemistry, and Biology, within the context of global warming.

b. Observation and Documentation Results
Meaningful Stage (Competency Development)

At the meaningful stage, the project adopted a green chemistry theme through activities focused on processing household waste, specifically converting used cooking oil into soap. This project was not merely intended as a practical solution, but also served to motivate students to develop greater awareness of the importance of waste management and to recognise that waste can gain value when deliberately processed responsibly.



Figure 6. The Process of Making Soap from Used Cooking Oil

During this project-based learning session, the activities were examined not only from the perspective of chemical processes but also emphasised students' ability to measure materials during saponification accurately. Appropriate proportions were required to produce soap that was not only successfully formed but also had a pH level safe for use.

The assessment instruments were described in the guidelines and rubrics used to analyse and evaluate students' project documentation. These documents included project reports, presentations, and student prototypes. The assessed aspects covered the overall quality of students' project outputs, including written reports, presentations, and final products.

Table 10. Soap Project Assessment Rubric

Group	Product Outcome	Notes	Category
1	Soap with an appealing colour, safe for use	Soft texture, appropriate colouring	Developing as Expected
2	Soap with a distinctive olive aroma, soft texture	Excess olive oil	Beginning to Develop
3	Fragrant soap, stable emulsion, safe pH	Texture not yet solid, but usable	Highly Developed
4	Soap with an appealing colour, safe for use	Soft texture, appropriate colouring	Developing as Expected

Observational results indicate according to the table; (1) Group 1 successfully produced soap with a visually appealing emulsion and harmonious colour due to the appropriate use of colouring agents. Although the texture was soft, the soap was safe to use because the sodium hydroxide content was sufficient.

Category: Developing as Expected.

(2) Group 2 produced soap with a soft texture and incomplete emulsion due to excessive olive oil. However, the aroma of olive oil and lemongrass oil effectively masked the odour of used cooking oil, resulting in a product with positive value.

Category: Beginning to Develop.

(3) Group 3 successfully produced fragrant soap with a stable emulsion and a pH level that met safety standards. Although the texture was not yet fully solid – possibly due to an imprecise proportion of sodium hydroxide the product was generally suitable for use.

Category: Highly Developed.

(4) Group 4 produced soap with an appealing colour and a safe pH level. The texture was relatively soft, but the soap remained safe for use due to appropriate material proportions.

Category: Developing as Expected.

Mindful Stage (Awareness Development)

The integration of the three science disciplines added a holistic dimension to the learning process. Physics provided a foundation for understanding measurement and energy concepts, chemistry contributed practical green chemistry approaches through recycling used cooking oil into soap, and biology offered natural mitigation solutions through greening projects and tree planting as carbon compensation efforts.

Beyond these activities, the project was also linked to handwashing practices in the school environment as a preventive measure against the spread of viruses and bacteria, aligning with the Grade X Phase D biology curriculum on viruses. This synergy was reflected in the quality of the soap products made from waste oil, the development of carbon filter prototypes as final projects, and observable behavioural changes, such as students' participation in tree-planting activities, particularly among those identified as having higher carbon emissions.

Such multidisciplinary integration aligns with the existing literature, which emphasises cross-disciplinary cocurricular science education with an environmental perspective as an effective approach for fostering 21st-century competencies and environmental literacy.

Joyful Stage (Enjoyable Learning)

The implementation of a reward-based model following the successful completion of environmental care projects included an outing class and a visit to PLTU UP Indramayu. This activity was complemented by meaningful corrective actions, such as requiring two students with above-average carbon footprints to plant trees. This approach reflects principles of restorative pedagogy, where corrective measures are not merely punitive but are designed to offset environmental impacts through pro-environmental actions.

Students whose carbon emissions exceeded the average were allowed to restore their impact by planting trees within the school environment, thereby fostering responsibility and environmental stewardship. The medium-term impact of this approach can be evaluated through observations of tree growth and follow-up assessments of behavioural changes, both self-reported and directly observed.

From a theoretical perspective, these reflective actions align with the concept of behavioural nudges in environmental education, whereby clear, measurable, and meaningful consequences encourage the internalisation of pro-environmental norms. The DL-CEP learning activities concluded with a reflective session and the cultivation of ecological awareness through a visit to PLTU Indramayu on 6 October 2025,

which provided students with a real-world context for public debates on sources of pollution.



Figure 7. Power Plant Visit to Reduce Carbon Emissions Literacy



Figure 8. Student Participation in Mangrove Planting

Exposure to emission control practices at the power plant, including the use of continuous emission monitoring systems, shifted students' attribution frameworks from the assumption that "industry is the sole major polluter" toward a more nuanced understanding that local emission sources also originate from agricultural activities, such as straw burning, and household waste. This broader perspective enabled students to recognise the multifaceted nature of carbon emissions within their immediate environment.

The study revealed significant increases in students' average scientific skill scores ($\Delta = +13.0$) and environmental care attitude scores ($\Delta = +38.0$) following the deep learning-based carbon-emission intervention. This instructional approach integrated the use of a carbon footprint website, interdisciplinary science projects (Physics-Chemistry-Biology) focused on waste processing and carbon filter media, and field-based literacy activities through a power plant outing class.

The obtained effect sizes (Cohen’s $d \approx 0.85-0.92$) indicate a large intervention effect on both variables.

These findings are consistent with the work of Safiati et al., who reported that deep learning designs connecting real-world data, collaborative practice, and reflective activities have the potential to generate more durable changes in students’ attitudes and competencies. The observed improvements align with the deep learning framework that emphasises meaningful understanding, reflective awareness (mindfulness), and enjoyable learning experiences (joy). The integration of personal data reflection (carbon footprint calculations), collaborative projects, and artifact production (green soap and mini carbon filter prototypes) strengthened both cognitive and affective student engagement, there by facilitating the internalisation of environmental values, as also highlighted in recent studies.

Furthermore, these results support the findings of Hakim (2020) who demonstrated that science learning grounded in environmental issues is effective in fostering students’ attitudes of environmental care. When scientific content is closely connected to everyday experiences, students are more likely to internalise values of environmental responsibility. In this study, students’ engagement with a carbon footprint calculator and environment-based projects heightened their awareness of the real-life implications of carbon emissions.

Learning models that employ digital media to measure personal carbon footprints and respond

through tangible projects and reflective actions, such as tree planting, offer a promising response to the persistent challenges of environmental literacy in secondary education. Previous studies have noted that environmental literacy in senior high schools is often constrained by difficulties in linking knowledge to action (Saputri, 2024). Methodologically, the use of digital tools that reflect personal data helps bridge the gap between theoretical concepts and students’ lived experiences, thereby supporting the development of actionable knowledge. This explains why the interdisciplinary, project-based deep learning intervention produced a large effect: it not only conveyed knowledge but also required reflective actions, as evidenced by concrete project outputs.

The project involving the conversion of used cooking oil into soap demonstrated that students were not only able to understand theoretical concepts but also to apply the principles of green chemistry in practice. Several key outcomes were identified: (1) improved practical skills, as students were able to follow experimental procedures, use equipment appropriately, and produce tangible products; (2) enhanced creativity, reflected in variations across groups in color, fragrance, and emulsion quality; (3) effective group collaboration, evidenced by clear role distribution in reporting, implementation, and documentation; and (4) growing environmental awareness, as students recognized the importance of transforming household waste into useful products rather than treating it merely as refuse.

Table 11. Integration of Data

Quantitative Data	Qualitative Data	Documentation
1) Scientific skills (Wilcoxon test) 2) Environmental care attitudes (Paired Sample t-test)	Interviews with the science teacher/laboratory coordinator, the biology teacher, and the physics teacher	Photographs and Rubrics of Soap project (Making activity using cooking oil waste)
Questionnaire scores showed a significant increase. Large effect size increases scientific competencies and environmental care attitude (posttest -pretest)	Direct Observation of Students by the Observing Teacher Positive statements from teachers	Carbon footprint data entry via JejakKarboku.id Students’ Enthusiasm in Discussions with Chemistry -Environmental Experts (PLTU) and Mangrove Planting Activities

The significant improvement in students’ scientific skills is consistent with project-based learning research, including a study by Zubaidah (2020), which emphasises the role of collaborative learning in developing 21st-century competencies. Qualitative analysis of students’ understanding of carbon emission concepts further supports the conclusion that this learning approach facilitated tangible changes in students’ environmental awareness, as reflected in their project outcomes. Indicators supporting this assessment included: (a) accuracy in applying carbon emission

reduction concepts within projects; (b) creativity and innovation in proposed solutions; (c) quality of reports and presentations in terms of organization, clarity, and completeness; (d) students’ ability to integrate information from multiple disciplines; and (e) understanding of problem-solving processes within project contexts. These findings align with (Hidayat & Haryati, 2025), who reported that DL-CEP learning strengthens conceptual understanding, enhances critical thinking skills, and increases student engagement.

Knowledge gained from the power plant visit further enriched students' understanding of carbon emissions. An assistant environmental manager explained that at the local level, observation activities and environmental monitoring programs conducted by the Indramayu Environmental Agency provide real-time emission data that are reported up to the Ministry of Environment, enabling empirical validation of industrial emission control. At the same time, students were encouraged to critically reflect on overlooked non-industrial sources of emissions, such as straw burning, which contributes to seasonal pollution. Dense haze frequently affects western Indramayu during the rice harvest season, according to the Indramayu Environmental Agency (Yuliana, 2018).

This information serves as a valuable stimulus for aligning school curricula with locally relevant environmental solutions and for strengthening action-oriented learning. The carbon emission learning activities concluded with a reflective action: a collaborative mangrove planting initiative in abrasion-prone coastal areas at Ujung Ori Beach, Patrol District, Indramayu. This activity further reinforced students' ecological awareness and contributed to the development of a strong character of environmental care.

The integrated data table also confirms and follows up on cocurricular project activities, including the revitalisation of the school waste bank program that had previously stagnated. This initiative played an important role in fostering a learning ecosystem that is enjoyable, meaningful, and empowering, thereby enabling students to develop as well-rounded individuals. These findings are consistent with the Ministry of Education's definition of deep learning, which emphasises a human-centred approach to learning through mindful, meaningful, and joyful learning environments.

Within the framework of deep learning, this approach is closely associated with holistic education. As noted by Cendana (2025), by focusing on the core principles of deep learning, educators can create learning environments that not only emphasise academic achievement but also support the development of students' social and emotional skills.

Conclusion

This study demonstrates that the Deep Learning-Carbon Emission Project (DL-CEP) is effective in enhancing students' scientific competencies and environmental care attitudes through the integration of project-based deep learning, digital carbon emission analysis, interdisciplinary science learning, and field-based experiences. Students' direct engagement with

real-world environmental data and industrial practices increased the relevance and meaningfulness of learning within the local context.

The main contribution of this study lies in the integration of deep learning, carbon emission analysis, and interdisciplinary science projects within a single, technology-supported framework that simultaneously improves both cognitive competencies and environmental attitudes.

Based on the results and discussion, it can be concluded that 1). DL-CEP learning had a significant effect with a large effect size on the improvement of students' scientific skills; 2) DL-CEP learning had a significant effect with a large effect size on students' environmental care attitudes; and 3) The implementation of DL-CEP learning was effective in enhancing both scientific competencies and positive changes in environmental care attitudes throughout the global warming learning sequence.

However, this study is limited by the use of a one-group pre-experimental design without a control group, which restricts the generalisation of causal relationships. Practically, the DL-CEP model can be implemented in other schools by adapting key components such as digital carbon footprint tools, project-based interdisciplinary activities, and contextual environmental issues aligned with local conditions. This approach supports the development of 21st-century skills and sustainable behaviour among students. Future studies are recommended to employ experimental designs with control groups, involve larger and more diverse samples, and examine the long-term impact of DL-CEP. Further research may also explore the integration of advanced technologies, additional learning variables, and the application of DL-CEP across different subjects and educational contexts.

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Author Contributions

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Conflicts of Interest

The author declares no conflict of interest.

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