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Integrating Authentic Carbon Balance Data into Environmental Science Learning through CarbonXplorer

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Abstract

Background: Environmental literacy is an essential competency for addressing contemporary environmental challenges. However, university students often experience difficulties interpreting authentic environmental data and applying scientific evidence to environmental decision-making. Although digital learning media have been widely developed, the integration of authentic carbon balance data derived from land-use change analysis into Environmental Science learning remains limited.
Methods: This study aimed to develop CarbonXplorer, a digital learning platform that integrates carbon balance data derived from land-use change analysis into Environmental Science learning, and to evaluate its validity and practicality. The platform was developed using the ADDIE instructional design model. Product validity was assessed by five experts covering content, media and interface, learning design, environmental literacy, and interactivity. Practicality was evaluated through a limited implementation involving university students.
Results: CarbonXplorer integrates land-cover maps, carbon stock information, carbon balance analysis, interactive simulations, and reflective learning activities into a single inquiry-oriented learning platform. Expert evaluation indicated an overall validity score of 90.50% (highly valid), with the highest ratings for environmental literacy (93.75%) and content quality (93.13%). Limited implementation demonstrated that the platform was highly practical, achieving an overall practicality score of 86.71%, with the highest ratings for interactivity and exploration (88.50%) and content quality (87.25%).
Conclusion: CarbonXplorer provides an authentic digital learning environment by transforming carbon balance data derived from land-use change analysis into meaningful learning experiences. By integrating carbon balance data with inquiry-based learning activities, the platform has the potential to support learning experiences aligned with environmental literacy competencies, particularly in interpreting environmental evidence and making evidence-based environmental decisions.

INTRODUCTION

Environmental challenges in the twenty-first century have become increasingly complex as human activities continue to alter ecosystem balance. Land-use change, deforestation, and increasing carbon emissions have disrupted the global carbon cycle and accelerated climate change (Achmad et al., 2023; Calvin et al., 2023; Gitima et al., 2025; Li et al., 2024). In Indonesia, approximately 32 million hectares of tree cover have been lost since 2001, reducing ecosystem carbon sequestration capacity and exacerbating greenhouse gas emissions (GFW, 2025). These conditions indicate that addressing environmental problems requires not only technological innovation but also individuals who are capable of understanding the interactions between human activities and environmental change and making responsible decisions to support environmental sustainability.

These competencies are reflected in the concept of environmental literacy, which encompasses the knowledge, dispositions, competencies, and environmentally responsible behaviors required to understand and address environmental issues (Wheaton et al., 2018). Environmental literacy is widely recognized as a key competency for achieving sustainable development because it enables individuals to interpret scientific evidence and apply it to environmental decision-making (Fang et al., 2023). However, previous studies have consistently reported that university students' environmental literacy remains moderate and requires further improvement. Although students generally understand fundamental environmental concepts, they often experience difficulties interpreting environmental data, evaluating the impacts of human activities, and formulating evidence-based environmental solutions (Anggraini & Nazip, 2022; Irawati et al., 2023; Yusup, 2021). These findings highlight the need for learning approaches that provide learning experiences through the investigation and exploration, thereby strengthening students' analytical and evidence-based decision-making skills.

Environmental education in higher education plays a crucial role in fostering students' environmental literacy. Integrating environmental issues into higher education curricula has been shown to enhance students' understanding of sustainability principles and ecological responsibility (Ankareddy et al., 2025; Gamage et al., 2022). Nevertheless, environmental learning remains predominantly concept oriented, providing limited opportunities for students to investigate real environmental phenomena more broadly. Consistent with these challenges, the analysis of students' performance in the Environmental Science learning indicated that the expected learning outcomes had not yet been achieved. This reveals a gap between the intended learning outcomes specified in the syllabus and students' actual performance. This finding was reinforced by the needs analysis, which indicated the need for more interactive and exploratory learning experiences. Therefore, learning resources should extend beyond conceptual explanations by enabling students to investigate environmental problems, explore authentic environmental data, and evaluate alternative solutions based on scientific evidence. Such learning experiences are consistent with the competencies emphasized in environmental literacy, particularly environmental analysis and evidence-based decision-making.

Carbon balance associated with land-use change provides an authentic context for environmental science learning. It explicitly illustrates the relationship between human activities and ecosystem functioning. Carbon balance reflects the equilibrium between

carbon sequestration and carbon emissions and therefore provides a meaningful indicator for understanding the environmental consequences of land-use change. Changes in land cover directly influence vegetation structure, carbon storage capacity, and carbon emissions (Poorter et al., 2015; Zhu et al., 2021). Seluma Regency, Bengkulu Province, Indonesia, was selected as the study area because it has experienced substantial land-cover changes affecting regional carbon dynamics. According to Statistics Indonesia, the protected forest area in Seluma declined from approximately 66,330 ha in 2023 to 46,381.90 ha in 2024 (BPS, 2023, 2025). This environmental condition provides an authentic context for examining the relationship between land-use change and carbon balance. Consequently, environmental data derived from land-use change analysis, including carbon balance information, have considerable potential as authentic learning resources that enable students to interpret environmental information, analyze environmental changes, and formulate evidence-based environmental decisions.

Recent advances in remote sensing technology and digital learning environments provide new opportunities to transform land-use change and carbon balance data into meaningful learning resources. Remote sensing enables land-cover change and carbon dynamics to be analyzed spatially and temporally, providing authentic scientific evidence that can be integrated into environmental learning. Previous studies have demonstrated that digital learning media enhance students' engagement, conceptual understanding, and learning experiences in science education (Aspariga et al., 2024; Bashith et al., 2024; Luthfi et al., 2023). Likewise, learning environments that utilize authentic environmental contexts improve the relevance and meaningfulness of environmental education (Clayton et al., 2019; Sriyati et al., 2022; Wahyuni et al., 2022). Despite these advances, most existing digital learning media primarily emphasize conceptual explanations, environmental visualization, or information delivery. The integration of authentic land-use changes and carbon balance data that enables students to explore and make evidence-based decisions remains limited.

Therefore, a significant gap remains in the development of digital learning media for environmental education. Most existing studies focus on developing instructional media that present environmental concepts or visualize environmental phenomena, whereas the integration of land-use change and carbon balance data as authentic learning resources has received little attention (Hajj-Hassan et al., 2024; Husamah et al., 2025; Samitra et al., 2026). As a result, students have limited opportunities to explore authentic environmental data and use scientific evidence to analyze environmental problems and evaluate alternative solutions. Transforming environmental research findings into authentic learning resources has the potential to bridge the gap between classroom concepts and real-world environmental issues while supporting learning experiences aligned with environmental literacy competencies.

To address this gap, this study developed CarbonXplorer, a digital learning platform that integrates land-use change and carbon balance data into Environmental Science learning. CarbonXplorer enables students to explore land-cover change, interpret carbon stock dynamics, evaluate regional carbon balance, simulate alternative land-use scenarios, and reflect on environmental consequences using authentic scientific evidence. Consequently, CarbonXplorer functions not merely as an information delivery medium but as an inquiry-oriented digital learning platform that transforms environmental research data into authentic learning experiences. Through the integration of land-use change and carbon balance data with inquiry-based learning activities, CarbonXplorer is intended to

support competencies associated with environmental literacy, particularly environmental analysis and evidence-based decision-making. The purpose of this study was to develop CarbonXplorer, a digital learning platform integrating land-use change and carbon balance data into Environmental Science learning, and to evaluate its validity and practicality.

METHODS

This study employed a Research and Development (R&D) approach using the ADDIE instructional design model proposed by Branch, which consists of five phases: Analysis, Design, Development, Implementation, and Evaluation (Branch, 2009). The model was used to guide the systematic development of CarbonXplorer. During the Analysis phase, instructional needs were identified through curriculum analysis and course learning outcomes, students' learning needs, and carbon balance data. The Design phase focused on designing learning activities, platform structure, and research instruments. In the Development phase, CarbonXplorer was developed and validated by expert validators before being revised based on their recommendations. The Implementation phase involved a limited trial to evaluate the practicality of the platform, whereas the Evaluation phase consisted of revising the product based on expert feedback and students' responses. The overall research procedure is illustrated in Figure 1.

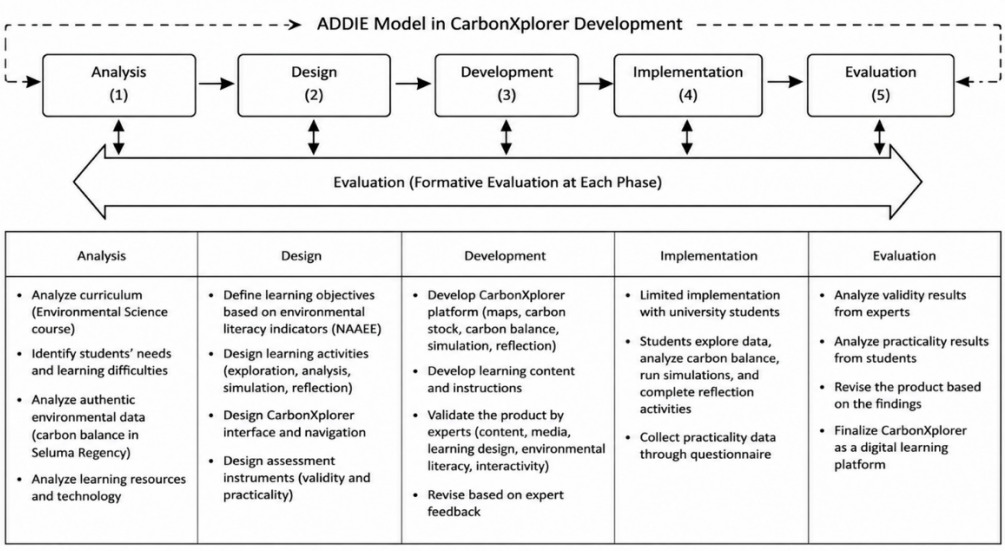


Figure 1. Research Procedure Using ADDIE Model

Data were collected using three research instruments: a needs analysis questionnaire, a product validation sheet, and a student response questionnaire. The needs analysis questionnaire was administered to identify students' learning needs and instructional problems in Environmental Science learning. Product validity was evaluated by expert validators using a validation sheet covering five assessment aspects: learning content, media and interface, learning design, environmental literacy, and interactivity. Product practicality was assessed using a student response questionnaire following the limited implementation of CarbonXplorer. The collected data were analyzed using descriptive quantitative analysis. Product validity and practicality were assessed using a four-point Likert scale, where 4 = strongly agree, 3 = agree, 2 = disagree, and 1 = strongly disagree. Percentage scores were calculated using:

$$\text{Percentage} = \frac{\text{Obtained Score}}{\text{Maximum Score}} \times 100\%$$

The percentage scores were interpreted according to the validity and practicality criteria proposed by Akbar (2013) presented in Table 1.

Table 1. Validity Criteria of CarbonXplorer

Percentage (%)	Validity Criteria
85.1–100	Highly Valid
70.1–85.00	Valid
50.1–70.00	Moderately Valid
< 50	Less Valid

RESULT AND DISCUSSION

The analysis phase examined the instructional requirements for developing CarbonXplorer through curriculum analysis, student needs assessment, and learning resource analysis. The findings served as the basis for designing a digital learning platform that integrates authentic carbon balance data into Environmental Science learning. Curriculum analysis indicated that the Environmental Science course aims to develop students' understanding of human-environment interactions, environmental problem analysis, and solution-oriented thinking. Learning activities are primarily conducted through discussions, presentations, assignments, and project-based activities supported by presentation slides, videos, and the Learning Management System (LMS). Despite these learning activities, opportunities for students to investigate authentic environmental data and formulate evidence-based environmental decisions remain limited (Table 2).

Table 2. Summary of Curriculum Analysis

Curriculum component	Findings
Learning outcomes	Students are expected to understand the relationships between humans and the environment, analyze environmental problems, and propose appropriate solutions.
Learning activities	Discussions, presentations, assignments, and project-based learning.
Learning media	Presentation slides, videos, and Learning Management System (LMS).

These findings suggest that the existing learning process primarily supports conceptual understanding but provides limited opportunities for students to investigate authentic environmental phenomena using scientific evidence. Such learning conditions may constrain the development of higher-order environmental literacy, particularly students' ability to analyze environmental problems and formulate evidence-based decisions, which are recognized as essential competencies of environmental literacy (Hollweg et al., 2011; Kaya & Elster, 2019). The student needs assessment further reinforced these findings (Table 3). A total of 87% of students reported experiencing difficulties in Environmental Science learning, particularly in interpreting environmental data, analyzing environmental problems, and evaluating environmental conditions. Furthermore, 95% indicated the need for learning media that support environmental literacy, while 97% preferred interactive digital learning media capable of presenting environmental information through visual representations.

Table 3. Student Needs Assessment

Statement	Agreement (%)
Students experience difficulties in Environmental Science learning.	87
Students need learning media that support environmental literacy.	95
Students prefer interactive digital learning media.	97

These findings indicate that students require more contextual and interactive learning experiences to support Environmental Science learning. Previous studies have shown that learning environments incorporating authentic environmental information can improve students' engagement, analytical skills, and evidence-based decision making because students investigate real environmental problems rather than hypothetical cases (Bravo et al., 2016; Norton et al., 2019; Susilawati et al., 2021).

The curriculum analysis above indicated that Environmental Science learning requires students to analyze environmental problems and propose evidence-based solutions. This instructional need was reinforced by the student needs assessment, which revealed that many students experienced learning difficulties and expressed a strong preference for interactive digital learning media. Therefore, CarbonXplorer was developed to address these instructional needs by integrating authentic carbon balance data derived from land-use change analysis into inquiry-oriented learning activities.

The learning resource analysis examined the suitability of carbon balance data derived from land cover change analysis as authentic learning resources for the Environmental Science course. The dataset comprises spatial, temporal, and quantitative environmental information, including land cover maps, land cover statistics, carbon stock estimates, carbon balance data, and long-term environmental trends (Table 4). These characteristics enable students to investigate environmental change using authentic scientific evidence rather than hypothetical examples.

Table 4. Educational Potential of the Carbon Balance Dataset

Learning Resource	Educational Potential
Land cover maps	Identify spatial patterns of land cover change
Land cover statistics	Compare land cover composition across years
Carbon stock data	Analyze carbon storage capacity
Carbon balance data	Evaluate carbon source and sink dynamics
Temporal trends	Investigate long-term environmental change
Spatial visualization	Support evidence-based environmental reasoning

Carbon balance analysis of Seluma Regency revealed a continuous decline in carbon stock from 23,576,507.0 Mg C in 2005 to 19,024,867.7 Mg C in 2025, representing a total carbon loss of 4,551,639.3 Mg C. This decline was associated with continuous land-cover conversion, particularly the reduction of forested areas and the expansion of agricultural and built-up land, which are widely recognized as major drivers of carbon stock loss (Gemitzi et al., 2021; Paria & Kumari, 2026). Furthermore, Markov Chain prediction indicated that carbon stock is likely to decrease to 17,873,061.1 Mg C by 2035, suggesting that Seluma will continue to function as a carbon source if current land cover trends persist. These findings demonstrate that the carbon balance dataset not only represents environmental conditions quantitatively but also provides authentic evidence of long-term environmental change. Such characteristics make the dataset suitable for inquiry-oriented learning, where students are encouraged to investigate environmental phenomena,

interpret scientific evidence, and evaluate environmental problems using real-world data rather than simplified examples. The availability of authentic spatial and temporal environmental information aligns with the intended learning outcomes of the Environmental Science course by enabling students to interpret scientific evidence, analyze environmental issues, evaluate environmental conditions, and formulate evidence-based environmental decisions. These competencies are fundamental dimensions of environmental literacy (Hollweg et al., 2011). Therefore, the carbon balance dataset was selected as the primary learning resource integrated into CarbonXplorer to support inquiry-oriented learning and the development of environmental literacy.

Design Phase

The design phase translated the findings of the analysis phase into the pedagogical framework and interface design of CarbonXplorer. The platform was designed based on the environmental literacy framework proposed by the North American Association for Environmental Education (NAAEE), which comprises four domains: environmental knowledge, competencies, dispositions, and environmentally responsible behavior (Hollweg et al., 2011). These domains served as the pedagogical foundation for designing learning activities and interactive features that support the development of environmental literacy. The alignment between the environmental literacy domains and the corresponding learning features integrated into CarbonXplorer is presented in Table 5.

Table 5. Alignment of Environmental Literacy Domains with Carbonxplorer Features

Environmental literacy domain	Key component	Implementation in CarbonXplorer
Knowledge	Understanding land-use change, vegetation, biomass, carbon stock, and carbon balance concepts	Learning materials introducing land cover, biomass, carbon stock, and carbon balance concepts
Competencies	Environmental data interpretation, environmental analysis, and evidence-based evaluation	Interactive exploration of land cover maps, carbon trends, carbon balance analysis, and environmental data interpretation
Dispositions	Environmental awareness, environmental concern, and motivation for learning	Reflection activities encouraging awareness and concern for environmental change
Environmentally responsible behavior	Evidence-based environmental decision-making and responsible action	Scenario-based decision-making activities using evidence derived from carbon balance analysis

The mapping demonstrates that each environmental literacy domain is represented through specific learning activities within CarbonXplorer. This design ensures that the platform supports conceptual knowledge, development of analytical skills, environmental awareness, and evidence-based decision-making, which are considered essential dimensions of environmental literacy. Based on this framework, CarbonXplorer was organized into three main learning modules: Phenomena & Concepts, Exploration, and Reflection. These modules were designed to guide students through a sequential learning process beginning with contextual understanding, followed by environmental data investigation, and concluding with evidence-based reflection and environmental

decision-making. The Phenomena & Concepts module introduces land cover change, biomass, carbon stock, and carbon balance concepts as the scientific foundation for subsequent learning activities. The Exploration module provides interactive access to satellite imagery, land cover maps, carbon stock trends, carbon balance analysis, and land-use change simulations, enabling students to investigate environmental change using authentic datasets. The Reflection module encourages students to evaluate environmental issues and formulate evidence-based environmental recommendations.

The interface integrates spatial visualization, graphs, quantitative environmental information, and interactive learning activities to facilitate students' interpretation of authentic carbon balance data. Integrating multiple forms of environmental information within a single digital learning environment enables students to connect spatial patterns, temporal changes, and quantitative evidence during environmental investigations. According to multimedia learning theory, combining visual, textual, and interactive representations promotes meaningful learning by facilitating knowledge integration and supporting scientific reasoning(Mayer, 2020).

Development Phase

The development phase produced CarbonXplorer, a web-based learning platform that integrates authentic carbon balance data derived from land cover change analysis into Environmental Science learning. The platform comprises five main components: Welcome Page, Home Page, Phenomena & Concepts, Exploration, and Reflection. The functions of each component are summarized in Table 6.

Table 6. Main Components and Functions of CarbonXplorer

Component	Subcomponent	Function in Learning Activities
Welcome Page	Application logo, brief description, Start Exploration button	Introduces CarbonXplorer and provides an overview of the learning objectives before students begin the learning activities.
Home Page	Main navigation menu: Phenomena & Concepts, Exploration, Reflection	Provides access to all main learning modules within CarbonXplorer.
Phenomena & Concepts	Land cover change phenomena, carbon emission potential in Seluma Regency, concepts of land cover, biomass, carbon stock, carbon balance, and learning guidelines	Provides contextual information and scientific concepts as the foundation for interpreting environmental data during the exploration stage.
Exploration	Satellite imagery, land cover maps, carbon stock trend graphs, carbon balance analysis, and land-use change simulations	Enables students to explore, compare, and analyze land cover change and carbon dynamics using authentic environmental datasets.
Reflection	Reflective questions and evaluation activities	Encourages students to evaluate exploration results, consider the consequences of land cover change on carbon systems, and develop environmental awareness and evidence-based responses to environmental issues.

The interface of CarbonXplorer is presented in Figure 2.

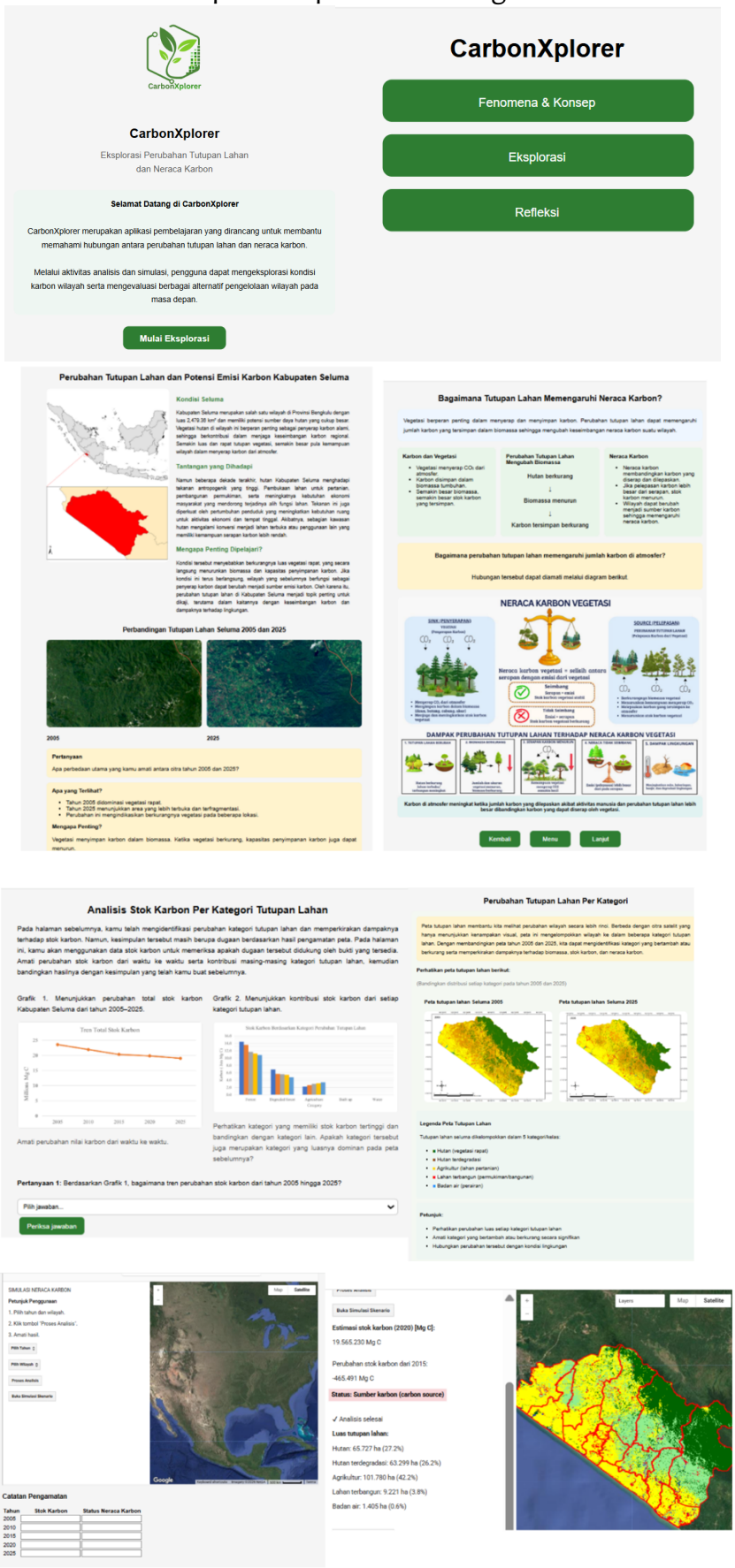


Figure 2. Main interfaces of CarbonXplorer

Figure 2 illustrates the user interface of CarbonXplorer, which is organized into five sequential modules: Welcome Page, Phenomena & Concepts, Exploration, Carbon Balance Simulation, and Reflection. The interface was designed to guide students through an inquiry-oriented learning process, beginning with contextual understanding of environmental issues, followed by exploration of authentic carbon balance data, interactive simulation of land-use change scenarios, and concluding with reflective evaluation and evidence-based environmental decision-making.

CarbonXplorer integrates land cover maps, satellite imagery, carbon stock graphs, carbon balance analysis, and interactive learning activities within a single digital learning environment. The integration of spatial, temporal, and quantitative environmental information enables students to investigate environmental change using authentic datasets rather than simplified examples. Interactive exploration of these datasets supports students in interpreting scientific evidence, analyzing environmental conditions, and formulating evidence-based environmental decisions.

The integration of authentic environmental datasets into a digital learning environment reflects the principles of inquiry-oriented learning, in which students actively construct knowledge through exploration and analysis of real-world environmental phenomena. Previous studies have shown that multimodal digital learning environments integrating textual, visual, and interactive representations enhance students' ecological literacy by improving conceptual understanding, critical thinking, and engagement with environmental issues. Such approaches also help students connect scientific concepts with real-world environmental phenomena (Lubis, 2025). Therefore, CarbonXplorer was designed not only as a learning medium but also as a digital environment that facilitates the development of environmental literacy through authentic environmental investigation.

Expert Validation

CarbonXplorer was evaluated by five expert validators representing expertise in biology education, environmental science, educational technology, and digital learning development. Product validity was assessed across five aspects: content, media and interface, learning design, environmental literacy, and interactivity. The validation results are presented in Figure 3.

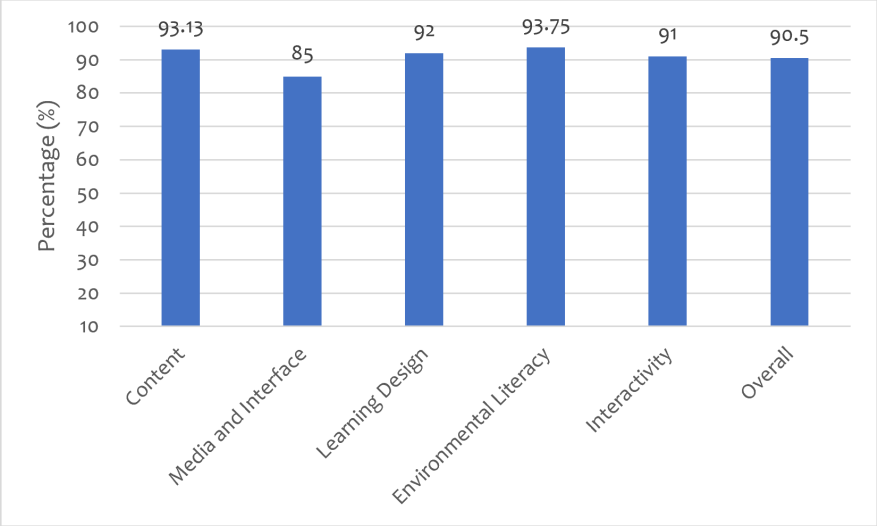


Figure 3. Expert Validation Results of CarbonXplorer

Overall, CarbonXplorer achieved an average validity score of 90.5%, indicating that the platform is highly valid for use in Environmental Science learning. The highest scores were obtained for the environmental literacy (93.75%) and content (93.13%) aspects, demonstrating that the integration of authentic carbon balance data effectively supports the intended learning objectives. The media and interface aspect received the lowest score (85%), suggesting that several interface improvements were required before implementation. The high validity scores indicate that CarbonXplorer successfully integrates environmental content, pedagogical design, and digital media into a coherent learning platform. The strong evaluation of the environmental literacy aspect confirms that the learning activities are consistent with the competencies proposed in the NAAEE environmental literacy framework. Meanwhile, the relatively lower score for media and interface highlights the importance of interface usability in maximizing students' interaction with digital learning environments. Previous studies have shown that intuitive navigation, well-organized content, and clear information presentation improve the usability and effectiveness of digital learning platforms by facilitating students' access to learning resources and reducing cognitive load (Ngampornchai et al., 2021; Tang et al., 2022).

Based on the validators' recommendations, several revisions were implemented to improve CarbonXplorer prior to the limited implementation phase. The revisions focused on strengthening carbon balance analysis, improving conceptual explanations, refining navigation, and enhancing interface usability. The revisions improved the clarity of environmental information, strengthened the presentation of scientific concepts, and enhanced user navigation. These improvements increased the usability of CarbonXplorer and better supported students' exploration and interpretation of authentic carbon balance data. Revising the platform based on expert feedback ensured that CarbonXplorer was pedagogically appropriate, scientifically accurate, and technically accessible before being implemented in classroom learning.

Students' Responses to CarbonXplorer

Following product development, CarbonXplorer was implemented on a limited scale to evaluate its practicality from the students' perspective. Students' responses were assessed across six aspects: content quality, spatial and data visualization, interactivity and exploration, support for environmental literacy, usability and navigation, and learning engagement. The results are presented in Figure 4.

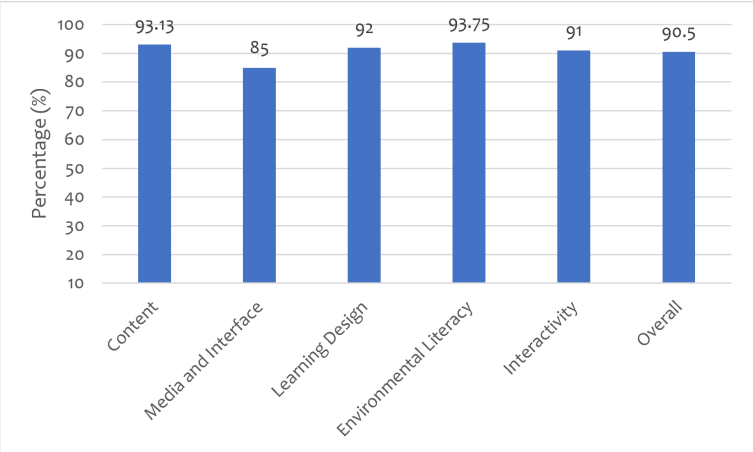


Figure 4. Students' Responses to CarbonXplorer

Students provided positive responses across all evaluated aspects, with interactivity and exploration receiving the highest score (88.50%). This finding indicates that the opportunity to explore authentic carbon balance data through interactive visualizations represents one of the principal strengths of CarbonXplorer. The integration of land cover maps, carbon stock information, and environmental analysis activities enabled students to engage directly with authentic environmental evidence throughout the learning process. Although usability and navigation obtained the lowest score (82.50%), the result still falls within the positive category. This finding suggests that the platform is generally easy to use while indicating opportunities for further refinement of navigation and interface organization. The result is consistent with expert validation, which also identified interface usability as an aspect requiring improvement.

Students' responses demonstrate that CarbonXplorer provides a meaningful learning experience by facilitating the exploration, interpretation, and evaluation of authentic environmental data. The integration of carbon balance information into inquiry-oriented learning activities supports the development of environmental literacy by encouraging students to analyze environmental evidence and formulate evidence-based environmental decisions, consistent with the competencies outlined in the NAAEE framework.

CONCLUSION

This study developed CarbonXplorer, a digital learning platform that integrates authentic carbon balance data derived from land-use change analysis into Environmental Science learning. CarbonXplorer integrates land-cover maps, carbon stock information, carbon balance analysis, interactive simulations, and reflective learning activities into a single inquiry-oriented learning platform. Expert evaluation indicated an overall validity score of 90.50% (highly valid), with the highest ratings for environmental literacy (93.75%) and content quality (93.13%). Limited implementation demonstrated that the platform was highly practical, achieving an overall practicality score of 86.71%, with the highest ratings for interactivity and exploration (88.50%) and content quality (87.25%). Future research should evaluate the effectiveness of CarbonXplorer across broader educational settings, particularly in enhancing competencies related to environmental data interpretation, environmental analysis, and evidence-based environmental decision-making. Future studies may also explore the integration of real-time environmental data. A key challenge for future development will be ensuring that complex and continuously updated environmental information can be presented in a way that remains accurate, accessible, and meaningful for learning.

DECLARATION OF GENERATIVE AI

During the preparation of this work, the authors used OpenAI to assist in language refinement, grammar checking, and sentences structuring. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

CONFLICTING INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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AUTHORSHIP CONTRIBUTION STATEMENT

Mustika Elmi Dayana: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing - Original Draft. **Euis Nursaadah**: Supervision, Validation, Methodology, Writing - Review & Editing. **Abdul Rahman Singkam**: Supervision, Validation, Writing - Review & Editing.

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