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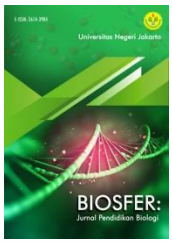

Development of AR flashcards to improve students' ESD-based analytical skills in biology

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ABSTRACT

The integration of digital technology in education has created opportunities for developing interactive learning media that support 21st-century competencies, including analytical thinking skills. Augmented Reality (AR) is one of the emerging technologies that can provide interactive and contextual learning experiences through 3D visualization. This study aims to develop AR-based flashcard media to improve students' ESD-based analytical skills. The study used the R&D method with the ADDIE model, involving 30 of 10th-grade students at *SMA Laboratorium Universitas Syiah Kuala* in the 2025/2026 academic year. The research instruments included an expert validation sheet, a System Usability Scale (SUS) questionnaire, a teacher and student response questionnaire, and an analytical skills test. The validation results indicated that the AR-based flashcard media was feasible for classroom implementation, obtaining scores of 77.40% from the material expert and 87.40% from the media expert. Positive responses were also obtained from the teacher (94.00%) and students (89.60%), while the System Usability Scale (SUS) score of 80.1 indicated an excellent level of usability. Furthermore, the analytical thinking skills test yielded an average N-Gain score of 0.57, which falls within the medium category. These findings indicate that the AR-based flashcard media is feasible, highly practical, and effective at a medium level in improving students' analytical thinking skills at the senior high school level. Therefore, the developed media can be used as an alternative learning media to support the implementation of Education for Sustainable Development (ESD).

INTRODUCTION

Education plays a crucial role in preparing individuals to address global challenges and contribute to sustainable development (Sari et al., 2025). In the era of globalization and the Industrial Revolution 4.0, education is expected not only to facilitate the acquisition of knowledge but also to foster twenty-first-century competencies, including critical thinking, creativity, collaboration, and technological literacy (UNESCO, 2018). One educational approach that supports these competencies is Education for Sustainable Development (ESD), which aims to equip learners with the knowledge, skills, values, and attitudes necessary to promote sustainable development and address environmental, social, and economic challenges responsibly (Rieckmann, 2018).

ESD seeks to integrate sustainability principles into educational practices, enabling learners to understand the interconnections among environmental, social, and economic systems and to make informed decisions for a sustainable future (Wajdi et al., 2024). According to UNESCO (2017), Education for Sustainable Development (ESD) emphasizes eight key competencies that learners need to address sustainability challenges effectively, namely systems thinking, anticipatory competency, normative competency, strategic competency, collaboration competency, critical thinking competency, self-awareness competency, and integrated problem-solving competency.

One important competency closely related to sustainable development is analytical skills. Analytical skills enable students to identify relationships among concepts, evaluate evidence, and formulate logical conclusions based on available information (Sholikhati & Sartika, 2022). In biology education, analytical skills are particularly important because students are required to understand complex scientific phenomena and evaluate environmental issues from multiple perspectives. However, previous studies indicate that the analytical skills of Indonesian senior high school students remain relatively low, partly due to limited opportunities to engage in problem-based learning and higher-order thinking activities (Blegur et al., 2023).

To support the implementation of ESD and enhance students' analytical skills, innovative learning media are needed. One promising technology is Augmented Reality (AR), which integrates virtual objects into real-world environments and allows users to interact with digital content in real time (Ariso, 2017). AR has been increasingly adopted in education because it can improve students' engagement, motivation, and conceptual understanding by visualizing abstract concepts in an interactive manner. Among various learning media, flashcards have also been widely recognized as effective tools for promoting active learning, supporting memory retention, and facilitating concept comprehension (Inayah et al., 2023).

The integration of AR technology into flashcard media provides opportunities to create more interactive and meaningful learning experiences. Through AR-based flashcards, static information can be transformed into three-dimensional visualizations, animations, and interactive learning content that support students' understanding of complex concepts (Kasim et al., 2024). Such features are particularly relevant for climate change learning, which requires students to analyze environmental phenomena and understand their impacts from scientific and sustainability perspectives (Supriyanto et al., 2023).

Several studies have demonstrated the effectiveness of AR in enhancing students' engagement, motivation, and conceptual understanding in science education (Akçayır & Akçayır, 2017). However, most previous studies have focused primarily on cognitive achievement and conceptual understanding, while limited attention has been given to the development of ESD-based analytical skills through the integration of AR and flashcard media. Furthermore, studies examining AR-based flashcards in climate change learning within the framework of Sustainable Development Goal 13 (Climate Action) remain scarce (Garzón et al., 2019).

The urgency of this study is supported by the increasing demand for ESD implementation in schools and the need to strengthen students' sustainability competencies. Based on interviews with biology teachers at SMA Laboratorium Universitas Syiah Kuala, ESD has been implemented in biology learning since the 2023/2024 academic year. Nevertheless, teachers still face challenges in teaching sustainability-related concepts due to the limited availability of innovative learning media that effectively integrate ESD principles into classroom instruction. Similar challenges have been reported in previous studies, which found that teachers often experience difficulties in translating ESD principles into classroom practice due to limited pedagogical resources, instructional support, and appropriate teaching materials (Corres et al., 2024; Parry & Metzger, 2023). Furthermore, effective ESD

implementation requires learning approaches that actively engage students with complex sustainability issues and promote higher-order thinking skills (Dittrich, 2024; Monroe et al., 2019).

This study addresses the identified research gap by developing AR-based flashcard learning media integrated with ESD principles for climate change learning. Unlike previous studies that mainly examined the effects of AR on learning achievement and motivation, this study focuses on enhancing students' ESD-based analytical skills. Here is the formulation of the problem used to address the issue:
RQ1. How feasible is the AR flashcard learning media in terms of validity, practicality, and usability?
RQ2. How do students' analytical skills improve after using the ESD-based AR flashcard learning media?

METHODS

Research Design

The method used in this study was a Research and Development (R&D) approach based on the ADDIE model proposed by Branch (2009). This development model consists of five stages: Analysis, Design, Development, Implementation, and Evaluation.

Population and Sample

The target population comprised all Grade 10 students at SMA Laboratorium Universitas Syiah Kuala during the 2025/2026 academic year. A purposive sample of 30 students from class X IPAS 1 was selected for the implementation stage based on the research objectives and the suitability of the class characteristics. One biology teacher also participated in evaluating the practicality and usability of the developed AR-based flashcard media. The demographic characteristics of the participants are presented in Table 1.

Table 1
Demographics Data

Participant Type	Population Size	Sample Size	Sampling Technique
Grade 10 Students	All students	30	Purposive Sampling
Biology Teacher	1 (all)	1	Convenience Sampling

Instrument

Data collection instruments included expert validation sheets, teacher and student response questionnaires, the System Usability Scale (SUS) questionnaire, and an ESD-based analytical skills test. The questionnaires assessed teachers' and students' responses to the developed AR-based flashcards, while the analytical skills test measured students' ESD-based analytical skills. Validation was conducted by two experts, one specializing in biology education content and the other in educational media, using Likert-scale instruments that assessed content accuracy, instructional quality, visual design, usability, and alignment with Education for Sustainable Development (ESD) principles. The instruments demonstrated acceptable validity based on expert judgment and acceptable reliability (Cronbach's α = 0.769).

Procedure

The research procedure followed the ADDIE model proposed by Branch (2009), consisting of five stages: (1) analysis, identification of learning needs, instructional problems, and resources related to ESD-based climate change learning; (2) design, preparation of learning objectives, analytical skills indicators, assessment instruments, and media designs; (3) development, creation of AR-based flashcard media using Canva and Assemblr Edu, followed by expert validation and revisions; (4) implementation, testing of the developed media with 30 tenth-grade students and a biology teacher; and (5) evaluation, assessment of the validity, practicality, and effectiveness of the media in improving students' ESD-based analytical skills.

Figure 1. Research Procedure

Data Analysis Techniques

Measurement parameters encompassed four aspects: (1) content validity, assessed by expert judgment with a percentage threshold of ≥81% for "very feasible"; (2) media practicality, determined from the percentage of positive responses from teachers and students, with a threshold of ≥81% indicating "very practical"; (3) media usability, analyzed using the System Usability Scale (SUS) scoring procedure (Brooke, 1996) where scores >80.3 were categorized as excellent; and (4) students' analytical skills, measured using the normalized gain index formula (Hake, 1998). The criteria for obtaining the normalized gain index are shown in Table 2, according to Hake (1998).

Table 2
Normalized Gain Value Criteria

N (Gain)	Description
g > 0.70	Hight
0.70 ≥ g ≥ 0.30	Medium
g < 0.30	Low

RESULTS AND DISCUSSION

The needs analysis showed that the biology learning media used at the selected high school were limited to textbooks and PowerPoint presentations. According to the biology teacher, these learning media were not sufficient to help students understand and visualize complex environmental topics. Observation sheets and needs questionnaires also showed that these limitations reduced student engagement and hindered the development of analytical thinking skills, especially in identifying problems, analyzing causes, and linking solutions to sustainability issues. These findings align with previous studies showing that traditional 2D media are often less effective at explaining abstract scientific concepts and that digital technologies can support student engagement and higher-order thinking skills (Mardin et al., 2025; Zou et al., 2025).

To address these challenges, an Augmented Reality (AR)-based flashcard learning media was developed to improve students' ESD-based analytical thinking skills. The media combines text, images, three-dimensional (3D) visualizations, and contextual information to create a more interactive and meaningful learning experience. The design was developed based on curriculum objectives and indicators of analytical thinking, while visual elements were carefully arranged to support effective learning and information processing (Clark & Mayer, 2016). The media was created using Canva and integrated into the *Assemblr Edu platform*. Previous studies have shown that AR-based learning media can improve conceptual understanding and increase student engagement through interactive and immersive learning experiences (Ibáñez & Delgado-Kloos, 2018; Nengsih et al., 2023). The final AR-based flashcard learning media is presented in Figure 2.

(a) (b)

Figure 2. Developed AR-Based Flashcard Learning Media. a. Product packaging, b. Flashcard design.

The developed AR-based flashcard media was validated by a material expert and a media expert, yielding feasible and very feasible scores of 77.40% and 87.40%, respectively (Table 3). These results indicate that the developed media successfully integrates climate change content with appropriate visual design and technological features to support learning objectives. The higher media validation

score suggests that the AR features, visual appearance, and functionality were well designed to facilitate student learning activities.

Table 3
Validation Results of AR Learning Media

Evaluator	Score (%)	Category
Material Expert	77.40	Feasible
Media Expert	87.40	Very Feasible

Following revisions based on expert feedback, the AR-based flashcard media underwent a classroom trial with 30 tenth-grade students and one biology teacher at USK Laboratory High School. The practicality assessment yielded very high scores, with 94.00% from the teacher and 89.60% from the students (Table 4). These findings indicate that the media was perceived as highly practical, relevant, and easy to implement in classroom instruction.

Table 4
Teachers' and students' responses to the AR-based flashcard learning media

Respondent	Average (%)	Category
Teacher	94.00	Very Practical
Students	89.60	Very Practical

In addition to practicality, the usability of the AR-based flashcard media was evaluated using the System Usability Scale (SUS) questionnaire, administered to 30 students. The results presented in Table 5 show an average SUS score of 80.1, indicating that the media falls within the Acceptable category, with Grade B and an Excellent level of usability. This finding suggests that the AR-based media is easy to operate, user-friendly, and does not create technical barriers that could interfere with the learning process. High usability is essential because a well-designed interface allows students to focus on learning activities rather than on operating the technology itself (Harta et al., 2021).

Table 5
SUS Score Results

Description	Value
Number of Respondents	30.00
Total SUS Score	2402.50
Average SUS Score	80.10

Following the positive usability results, the effectiveness of the media in improving students' analytical thinking skills was examined using the normalized gain (N-Gain) formula based on pre-test and post-test scores. As shown in Table **6**, the average score increased from 66.80 in the pre-test to 88.50 in the post-test, resulting in an N-Gain score of 0.57, which falls within the medium category according to Hake (1998). This result indicates that AR-based flashcard media contributed meaningfully to improvements in students' analytical thinking skills.

Table 6
Normalized Gain Calculation Results

Average pre-test score	Average post-test score	N-gain	Category
66.80	88.50	0.57	Medium

To further examine the impact of the media on specific analytical thinking indicators, N-Gain scores were analyzed across three dimensions: distinguishing, organizing, and connecting. The results presented in Table 7, reveal that the greatest improvement occurred in the organizing indicator, which achieved a score of 81% and was categorized as high. This finding suggests that the structured presentation of information and the integration of AR visualization effectively supported students in organizing concepts into logical and systematic relationships. The ability to visualize interconnected

environmental phenomena may have facilitated cognitive organization processes and improved conceptual understanding (Noto et al., 2022).

Meanwhile, the distinguishing (57%) and connecting (68%) indicators were categorized as medium. The moderate improvement in distinguishing skills indicates that some students still had difficulty identifying essential information among multiple sources presented through the media. Similarly, although students demonstrated better ability to connect causes and consequences of climate change phenomena, developing broader systems thinking skills such as linking environmental issues with long-term social and economic impacts, may require additional instructional support and learning experiences (Shobah & Hariyono, 2023).

Table 7
N-Gain Scores of Students' Analytical Thinking Skills Across Three Indicators

Indicator	Average (%)	Std. Deviation	Category
Distinguishing	57	24.51	Medium
Organizing	81	22.63	High
Connecting	68	29.05	Medium

Overall, the combination of excellent usability (SUS = 80.1) and medium improvement in analytical thinking skills (N-Gain = 0.57) demonstrates the potential of AR-based flashcard media as an effective learning tool for Education for Sustainable Development (ESD). The integration of sustainability-oriented content with immersive AR visualization enables students to explore environmental issues more meaningfully and connect scientific concepts with real-world phenomena. According to Schmalstieg & Höllerer (2016), AR technology can present abstract concepts in a more concrete and interactive way, thereby facilitating students' understanding of complex environmental issues. Similarly, Siahaanaa & Nugraha (2024) reported that AR-assisted digital flashcards can enhance students' engagement and conceptual understanding through interactive visualization.

Furthermore, the media's contextual and experiential learning experiences encourage active engagement, critical reflection, and analytical reasoning. Vioreza et al. (2023) emphasized that ESD-oriented learning should foster students' awareness and understanding of sustainability issues, while Idrus & Usi (2024) highlighted the importance of developing competencies to support informed decision-making regarding environmental challenges. Therefore, the findings suggest that AR-based flashcard media can support the implementation of ESD and foster higher-order thinking skills in science learning, as also noted by Sukhdeve (2021).

CONCLUSION

This study concludes that the AR-based flashcard learning media developed through the ADDIE model is feasible, highly practical, and effective at a medium level in improving students' ESD-based analytical thinking skills. The media achieved feasibility scores of 77.40% from the material expert and 87.40% from the media expert, received very positive responses from the teacher (94.00%) and students (89.60%), and obtained an excellent usability score (SUS = 80.1). Furthermore, the N-Gain score of 0.57 indicates a medium improvement in students' analytical thinking skills, with the highest gain observed in the organizing indicator. These findings suggest that AR-based flashcard media can provide interactive, context-rich learning experiences that support students' understanding of climate change concepts and promote analytical thinking, making it a promising alternative for implementing Education for Sustainable Development (ESD) in science education. In addition, the results suggest that teachers can use AR-based learning tools to foster higher-order thinking skills and promote more meaningful learning in science education, particularly in abstract and complex topics.

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