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Development of Augmented Reality-Assisted Flashcards to Improve Tenth-Grade Students' Conceptual Mastery in Biology

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Abstract
The development of technology-enhanced instructional media is increasingly important in biology education, particularly for topics that require students to understand abstract ecological processes. This study aimed to develop augmented reality-assisted flashcards and examine their feasibility and effectiveness in improving tenth-grade students' conceptual mastery of ecosystem components and interactions. The study employed a Research and Development design using the ADDIE model, which consists of analysis, design, development, implementation, and evaluation. The participants involved material experts, media experts, language experts, biology teachers, and tenth-grade students at SMA Negeri 15 Bandar Lampung, Indonesia. Data were collected through needs analysis questionnaires, expert validation sheets, student response questionnaires, and pre-test and post-test measures of conceptual mastery. The product was developed using Canva and Assemblr Edu to integrate printed flashcards with interactive three-dimensional augmented reality objects. The validation results indicated that the media was highly feasible, with scores of 87.06% from media experts, 89.16% from material experts, and 86.60% from language experts. The effectiveness test showed that students in the experimental class achieved a higher N-Gain score than those in the control class, with an N-Gain of 0.82 in the high category compared with 0.50 in the moderate category. The independent-samples t-test also indicated a statistically significant difference between the two groups, with a significance value of 0.000. These findings suggest that augmented reality-assisted flashcards are feasible and effective as an innovative instructional medium for supporting conceptual mastery in biology learning. The study implies that integrating printed visual media with interactive digital objects can strengthen students' understanding of abstract biological concepts and provide a more engaging learning experience.

Keywords: Augmented Reality; Biology Learning; Conceptual Mastery; Ecosystem; Flashcards

INTRODUCTION

Science education in the twenty-first century is increasingly shaped by the need to provide learning experiences that are not only informative but also interactive, contextual, and conceptually meaningful (Osborne, 2007, 2013; Townley, 2018). In biology education, this demand is particularly urgent because many biological concepts cannot be fully understood through verbal explanation, textbook descriptions, or two-dimensional illustrations alone (Handoko et al., 2024; Reinke et al., 2021; Stanič & Špernjak, 2025; Teplá et al., 2022). Biology deals with living systems, ecological relationships, microscopic structures, and dynamic processes that often require students to construct mental models of phenomena that are invisible, complex, or difficult to observe directly (Momsen et al., 2022; Oktafiani et al., 2025; Reinke et al., 2021). Consequently, students may experience difficulties in developing deep conceptual mastery when learning is dominated by conventional explanation and static media

(Casandra et al., 2025; Gennen, 2023). This challenge becomes more critical in the context of curriculum transformation, including the transition from the 2013 Curriculum to the Merdeka Curriculum in Indonesia, which emphasizes flexible learning, student agency, digital competence, and the development of higher-order thinking skills (Ap et al., 2025; Priawasana & Subiyantoro, 2024; Walid & Masri, 2025). Therefore, teachers are expected to design learning environments that are aligned with students' characteristics, technological development, and the demands of meaningful science learning (Mena-Guacas et al., 2025; Oo et al., 2024).

Instructional media play a strategic role in supporting this transformation because they function as mediating tools between abstract concepts and students' cognitive structures (Hansen & Richland, 2020; Sanchez, 2025). Effective media can stimulate students' attention, organize information, facilitate visualization, and support the construction of knowledge through multiple representations (Hansen & Richland, 2020; Sanchez, 2025). In biology learning, media are not merely supplementary teaching aids; rather, they are essential components of the instructional system that connect learning objectives, content, teaching strategies, and assessment (Barata & Agilliana, 2025). When media are designed appropriately, they can help students move beyond memorization toward interpretation, explanation, analysis, and application of biological concepts. However, in many classroom contexts, including senior high school biology classes, the use of learning media is still limited to printed textbooks, simple visual aids, PowerPoint slides, or teacher-centred explanations. Such media may be useful for introducing factual information, but they are often insufficient for representing ecological interactions, biological structures, and dynamic processes that require spatial and systemic understanding (Abdulrahaman et al., 2020; Mariati, 2024; Sukenda et al., 2019).

One biology topic that requires strong conceptual visualization is ecosystem components and their interactions (Barata & Agilliana, 2025; Oktafiani et al., 2025). This topic requires students to understand not only the definitions of biotic and abiotic components but also the relationships among organisms, food chains, energy flow, ecological balance, and the interdependence between living organisms and their environment. These concepts are systemic and relational; therefore, students must be able to identify components, explain interactions, analyse patterns, and connect ecological processes to real-life environmental phenomena. When ecosystem learning is delivered through static pictures or verbal explanation alone, students may recognize terms without fully understanding how the components interact within a system. This condition can lead to fragmented knowledge and superficial conceptual mastery. Accordingly, innovative media are required to provide students with concrete, interactive, and visually rich representations of ecosystem concepts.

Flashcards are one type of visual learning medium that has long been used to support memory, recognition, and concept acquisition (Anggreani et al., 2025; Melani et al., 2023). Their concise format allows teachers to present keywords, images, definitions, and short explanations in a simple and accessible way (Parveen et al., 2021; Rincon-Flores et al., 2024). Flashcards are practical, portable, low-cost, and easy to use in individual, pair, or group learning activities. In addition, flashcards can support active recall and repeated exposure, both of which are important for strengthening students' understanding of key concepts (Huang et al., 2025; Paldy et al., 2025). Nevertheless, conventional flashcards also have limitations. They generally present static images and short texts, which may not adequately support students in understanding complex biological relationships. For topics that require spatial, dynamic, and process-oriented representation, conventional flashcards need to be enhanced with interactive digital features so that they can provide richer learning experiences.

Augmented Reality (AR) offers a promising technological solution to enhance conventional flashcards (Nuraisyah et al., 2021; Prastiti et al., 2025; Setiawan et al., 2025). AR is an interactive technology that overlays virtual objects onto the real world through digital devices such as smartphones or tablets (Al-Ansi et al., 2023; Arena et al., 2022; Shatokhin et al., 2025). Unlike Virtual Reality, which immerses users entirely in a virtual environment, AR maintains the physical learning environment while adding digital information, animations, or three-dimensional objects to it (Al-Ansi et al., 2023; Crogman et al., 2025). This characteristic makes AR particularly suitable for classroom learning because students can still interact with real learning materials while simultaneously exploring digital representations (Samuel J., 2025; Tian & Ironsi, 2025). AR has three essential characteristics: it combines real and virtual elements, operates interactively in real time, and represents objects in three-dimensional form. These features allow students to observe digital objects from various angles, manipulate visual representations, and connect abstract concepts with concrete experiences (Crogman et al., 2025; Silva et al., 2023; Thangavel et al., 2025).

The integration of flashcards and AR creates a hybrid learning medium that combines the strengths of printed visual media with the affordances of digital interactivity (Nurhikmah et al., 2024; Putri et al., 2024). Through AR-assisted flashcards, students do not only read short explanations and observe printed images, but they can also scan the cards using a smartphone to display three-dimensional objects, animations, or interactive visualizations (Morfidi & Iatraki, 2025; Setiawan et al., 2025). This combination can transform flashcards from static memory tools into dynamic conceptual learning tools. In ecosystem learning, for example, AR-assisted flashcards can help students visualize organisms, habitats, food chains, and ecological interactions in a more concrete and engaging manner. Students can observe objects from different perspectives, compare components, and discuss relationships among ecological elements. Such experiences may strengthen conceptual mastery because students receive information through verbal, visual, and interactive channels.

From the perspective of multimedia learning, AR-assisted flashcards can facilitate learning by providing multiple representations that complement one another. Textual information can provide conceptual explanations, printed images can support recognition, and three-dimensional AR objects can strengthen spatial and relational understanding (Hansen & Richland, 2020; Reinke et al., 2021). When these elements are designed coherently, they may reduce cognitive barriers and help students build integrated mental models. In addition, AR can support constructivist learning because students are actively involved in observing, questioning, interpreting, and constructing meaning from interactive visual experiences. Rather than passively receiving information from the teacher, students can explore learning objects directly and connect them with prior knowledge. This active engagement is highly relevant to science education, where conceptual understanding develops through inquiry, observation, explanation, and reflection.

Previous research has shown that AR-based media can improve students' motivation, attention, engagement, visual perception, and learning outcomes (Naufa Daffa Anwar et al., 2025; Prasetya et al., 2024). Studies on AR in science education suggest that interactive three-dimensional visualization can help learners understand abstract concepts more effectively than conventional media (Kusumaningrum et al., 2025; Sari et al., 2024). AR also has the potential to increase students' intrinsic motivation because it presents learning material in a more immersive and enjoyable format (Gill et al., 2023; Prasetya et al., 2024). In classroom practice, AR can encourage collaborative learning, stimulate discussion, and provide opportunities for students to explore concepts independently or in groups (Amalia, 2018; Gardeli & Vosinakis, 2025; Li, 2025). These advantages are particularly relevant for contemporary learners who are familiar with mobile technology and digital interaction (Pedraja-Rejas et al., 2024). However, the educational value of AR depends not only on technological novelty but also on pedagogical design. AR media must be aligned with learning objectives, students' cognitive development, curriculum content, and valid assessment of learning outcomes (Balcha et al., 2025; Tian & Ironsi, 2025).

Despite the growing interest in AR-based learning, several gaps remain in the existing literature and classroom practice. First, many AR learning media have been developed for early childhood or elementary education, while studies involving senior high school biology students remain relatively limited. Second, a considerable number of AR-flashcard studies focus on mathematics, language learning, or general science topics, whereas the use of AR-assisted flashcards for ecosystem components and interactions has not been widely examined. Third, previous studies often emphasize students' motivation, interest, or general achievement, but fewer studies specifically examine conceptual mastery as the main learning outcome. Conceptual mastery is important because biology learning should not only produce improved test scores but also enable students to explain, analyse, and apply biological concepts accurately. Therefore, further research is needed to develop AR-assisted flashcards that are content-specific, pedagogically validated, and empirically tested in biology classrooms.

Preliminary observations conducted in a senior high school in Bandar Lampung indicated that biology learning still relied substantially on conventional methods, especially when teachers explained theoretical material requiring deep understanding. Teachers had attempted to provide contextual experiences by inviting students to observe plants around the school environment, and simple media such as sticky notes were used to support group discussions. Printed textbooks remained the main learning source, while presentation media and laboratory facilities were used only when time and equipment allowed. Although these practices indicate teachers' efforts to support learning, they also reveal the need for more innovative, flexible, and visually rich media that can help students understand biological concepts more effectively. In this context, AR-assisted flashcards can serve as a practical alternative because they combine printed materials with digital visualization accessible through students' smartphones.

This study therefore develops augmented reality-assisted flashcards using Assemblr Edu and Canva to improve students' conceptual mastery of ecosystem components and interactions. Assemblr Edu was selected because it enables the creation of accessible AR learning objects without requiring complex programming skills, while Canva supports the design of visually attractive printed flashcards. The product developed in this study is expected to provide a learning medium that is practical for teachers, attractive for students, and relevant to the technological orientation of contemporary education. The novelty of this study lies in the integration of hardcard-based flashcards, AR visualization, and ecosystem content for tenth-grade biology learning, with conceptual mastery positioned as the main outcome. This distinguishes the study from previous research that primarily examined AR media for younger learners, non-biology topics, or motivational outcomes.

Based on the identified problems and research gap, this study aims to develop and evaluate augmented reality-assisted flashcards for biology learning in senior high school. Specifically, the study seeks to determine the feasibility of the developed media based on expert validation and to examine its effectiveness in improving students' conceptual mastery of ecosystem components and interactions. The findings are expected to contribute theoretically to the development of technology-enhanced biology learning media and practically to the provision of an innovative instructional tool that supports interactive, contextual, and meaningful learning. By integrating printed flashcards with AR-based three-dimensional visualization, this study offers an alternative approach for helping students understand abstract ecological concepts more concretely and for strengthening the quality of biology learning in the digital era.

METHODS

Research Design

This study employed an educational Research and Development design aimed at developing and evaluating augmented reality-assisted flashcards as instructional media for biology learning. The product was designed to support students' conceptual mastery of ecosystem components and interactions through printed flashcards integrated with three-dimensional augmented reality objects. The developed media could be accessed through smartphones using the Assemblr Edu platform. The development process followed the ADDIE model, which consists of five systematic stages: Analysis, Design, Development, Implementation, and Evaluation (Branch, 2009). This model was selected because it provides a structured framework for designing, validating, implementing, and evaluating instructional products. In this study, the ADDIE model enabled the researchers to identify classroom needs, design media aligned with curriculum objectives, develop and validate the product, implement it in a real classroom setting, and evaluate its feasibility and effectiveness.

Research Setting and Participants

The study was conducted at SMA Negeri 15 Bandar Lampung, located on Jalan Labuhan Dalam, Tanjung Senang District, Bandar Lampung, Indonesia. The research was carried out during the even semester of the 2024/2025 academic year. The population consisted of all tenth-grade students at SMA Negeri 15 Bandar Lampung. The sample was selected using cluster random sampling, in which intact classes were randomly selected from the population. The study involved two stages of product testing. The limited trial involved 10 tenth-grade students to obtain initial responses regarding the practicality, attractiveness, and usability of the developed media. The large-scale implementation involved two classes: an experimental class consisting of 35 students and a control class consisting of 35 students. The experimental class used augmented reality-assisted flashcards, whereas the control class received conventional biology instruction.

Development Procedure

The development procedure was conducted according to the five stages of the ADDIE model. Follow the Figure 1.

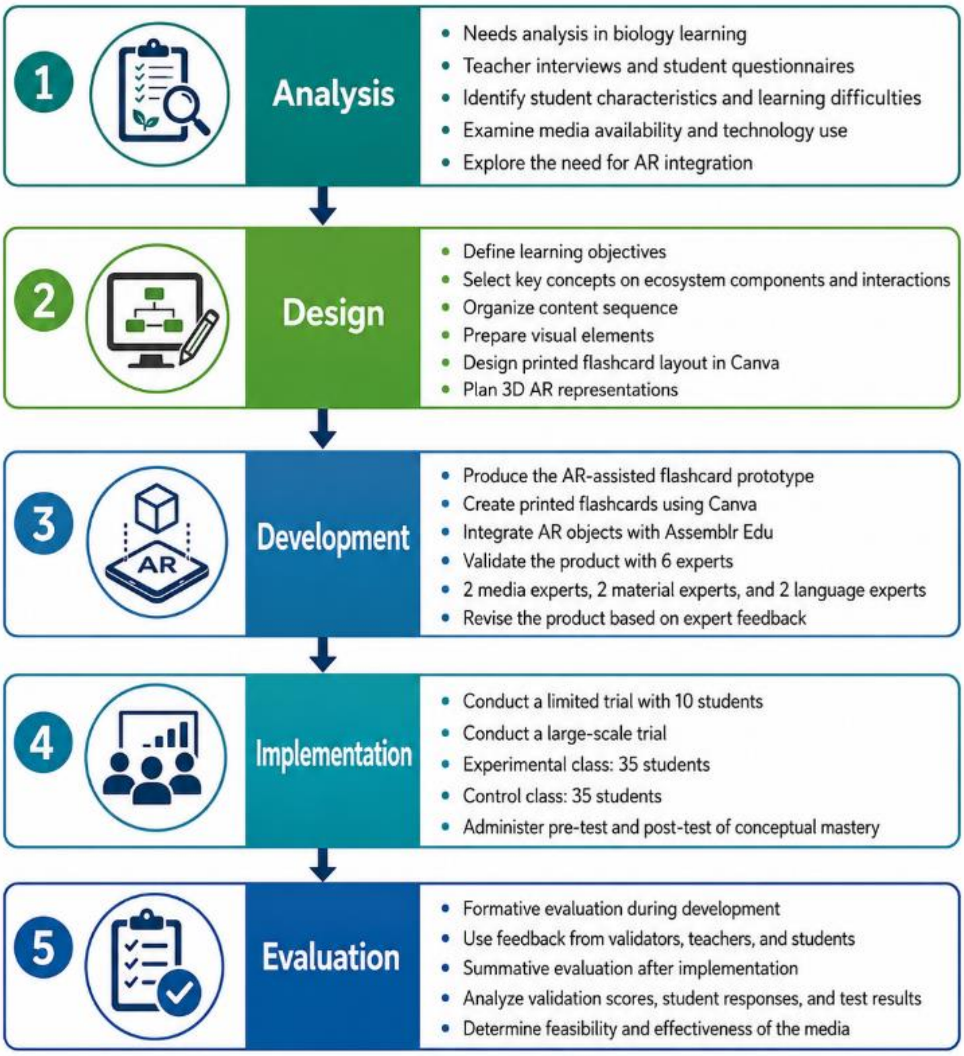

Figure 1. Five Stages of the ADDIE Model in Developing Augmented Reality-Assisted Flashcards

The first stage was Analysis. At this stage, the researchers conducted a needs analysis to identify problems in biology learning, students' characteristics, and the need for innovative instructional media. Data were collected through teacher interviews and student needs-analysis questionnaires. The analysis focused on the availability of learning media, students' difficulties in understanding ecosystem concepts, the use of technology in biology classrooms, and the potential integration of augmented reality into learning activities.

The second stage was Design. In this stage, the researchers designed the structure, content, and visual appearance of the flashcards. The learning material was focused on ecosystem components and their interactions. The design process included determining learning objectives, selecting key concepts, arranging the content sequence, preparing visual elements, and designing the printed flashcard layout using Canva. The augmented reality components were planned to support the visualization of biological objects and ecological interactions through three-dimensional digital representations.

The third stage was Development. At this stage, the prototype of the augmented reality-assisted flashcards was produced. The printed flashcards were designed using Canva, while the AR objects were integrated using Assemblr Edu. After the prototype was completed, the product was validated by experts. The validation involved six validators consisting of media experts, material experts, and language experts, with two validators for each area of expertise. The validators assessed the media in terms of visual design, technical quality, content accuracy, curriculum relevance, language clarity, readability, and suitability for tenth-grade students. Comments and suggestions from the validators were used to revise and improve the product before classroom implementation.

The fourth stage was Implementation. The revised product was implemented in biology learning with tenth-grade students. The implementation involved a limited trial and a large-scale trial. In the large-scale trial, the experimental class used augmented reality-assisted flashcards during the learning process, while the control class learned the same topic through conventional instruction. Before the intervention, both classes were given a pre-test to measure their initial conceptual mastery. After the learning activities, a post-test was administered to determine students' improvement in conceptual mastery.

The fifth stage was Evaluation. Evaluation was conducted both formatively and summatively. Formative evaluation was carried out during the development process by using feedback from validators, teachers, and students to revise the media. Summative evaluation was conducted after implementation by analysing expert validation scores, student responses, and pre-test and post-test results. The evaluation aimed to determine the feasibility and effectiveness of the developed media in improving students' conceptual mastery.

Research Instruments

The instruments used in this study consisted of expert validation sheets, student response questionnaires, teacher response questionnaires, conceptual mastery tests, and documentation. The expert validation sheets were used to assess the feasibility of the developed media from three perspectives: media design, material quality, and language appropriateness. The validation involved media experts, material experts, and language experts.

The student response questionnaire was used to obtain students' perceptions of the attractiveness, clarity, practicality, and usefulness of the augmented reality-assisted flashcards. The teacher response questionnaire was used to examine the suitability of the media for classroom use, its relevance to the biology curriculum, and its practicality in supporting learning activities.

The conceptual mastery test consisted of pre-test and post-test items related to ecosystem components and interactions. The pre-test was used to measure students' initial understanding before the intervention, while the post-test was used to measure students' conceptual mastery after the learning process. Documentation was used to record the development process, expert validation, classroom implementation, and product revision.

Data Collection Techniques

Data were collected through questionnaires, tests, interviews, and documentation. Questionnaires were used to collect data on needs analysis, expert validation, teacher responses, and student responses. Interviews were conducted with the biology teacher to obtain preliminary information regarding classroom conditions, learning media, students' learning difficulties, and the need for technology-based instructional media.

Tests were administered before and after the intervention to measure students' conceptual mastery. The pre-test and post-test were given to both the experimental and control classes. Documentation was used to support the research process by recording media development, validation activities, and implementation procedures.

Data Analysis

The data were analysed using quantitative and qualitative techniques. Quantitative data were obtained from expert validation scores, student response questionnaires, teacher response questionnaires, and conceptual mastery tests. Expert validation and response questionnaire data were analysed using a Likert scale and then converted into percentages to determine the feasibility and practicality of the developed media.

The feasibility percentage was calculated by comparing the obtained score with the maximum possible score. The results were then interpreted based on predetermined feasibility criteria, ranging from not feasible to highly feasible. This analysis was used to determine whether the augmented reality-assisted flashcards were appropriate for classroom implementation.

Students' conceptual mastery was analysed using pre-test and post-test scores. The improvement in students' conceptual mastery was measured using the normalized gain score. The N-Gain score was used to determine the level of improvement after the learning intervention and was categorized into low, moderate, or high improvement. In addition, an independent-samples t-test was used to examine whether there was a statistically significant difference between the experimental and control classes after the intervention. A significance level of 0.05 was used as the basis for decision-making.

Qualitative data were obtained from validator comments, teacher feedback, student suggestions, and observations during product implementation. These data were analysed descriptively and used to revise the media. The qualitative analysis helped identify weaknesses in the product design, content presentation, language clarity, and technical use of the AR features.

Through this combination of quantitative and qualitative analysis, the study was able to evaluate both the feasibility and effectiveness of the developed media. The quantitative data provided evidence of the media's validity, practicality, and impact on students' conceptual mastery, while the qualitative data supported product refinement and strengthened the interpretation of the development process.

RESULT AND DISCUSSION

Results

The development of augmented reality-assisted flashcards in this study was carried out through the ADDIE model, consisting of analysis, design, development, implementation, and evaluation. The final product was designed to support students' conceptual mastery of ecosystem components and their interactions by integrating printed flashcards with three-dimensional augmented reality objects through Assemblr Edu. The results of the study are presented in three main areas: expert validation, students' conceptual mastery, and the effectiveness of the developed media in comparison with conventional instruction.

Expert Validation of the Augmented Reality-Assisted Flashcards

The feasibility of the developed media was examined through expert validation involving media experts, material experts, and language experts. Each validation category was assessed in two stages: before revision and after revision. The two-stage validation process was intended to ensure that the product met the expected standards of instructional media quality before being implemented in classroom learning. The first validation stage provided initial information about the weaknesses of the prototype, while the second validation stage indicated the quality of the product after revision.

Table 1. Expert Validation Results of Augmented Reality-Assisted Flashcards

No.	Type of Validation	Stage 1 Before Revision	Stage 2 After Revision	Improvement
1	Media expert	67.05% Feasible	87.06% Highly feasible	**19.01%**
2	Material expert	61.66% Feasible	89.16% Highly feasible	**27.50%**
3	Language expert	62.50% Feasible	86.60% Highly feasible	**24.10%**
	Average	**63.74%**	**87.61%**	**23.87%**

The results in Table 1 show that all validation aspects increased substantially after revision. The average validation score increased from 63.74% in the first stage to 87.61% in the second stage, with an overall improvement of 23.87%. This finding indicates that the revision process contributed significantly to improving the quality of the augmented reality-assisted flashcards. The product was initially categorized as feasible, but after revision, it reached the highly feasible category. This improvement demonstrates that expert feedback played an essential role in refining the product before classroom implementation.

The highest improvement was found in the material validation aspect, which increased from 61.66% to 89.16%, showing an improvement of 27.50%. This result indicates that revisions related to content accuracy, curriculum alignment, conceptual clarity, and the suitability of biological material were particularly important in improving the quality of the product. Since the learning topic focused on ecosystem components and their interactions, the accuracy of concepts and the coherence of material presentation were crucial. In biology learning, inaccurate or oversimplified representations may lead to misconceptions; therefore, material validation became a central component in ensuring that the developed media could support valid conceptual understanding.

The media validation score increased from 67.05% to 87.06%, with an improvement of 19.01%. This increase indicates that revisions related to layout, visual quality, technical design, usability, and AR integration were effective in improving the media quality. The integration of printed flashcards with AR objects required not only attractive visual design but also functional compatibility between the printed card and the digital object. The revised media became more appropriate for use in biology learning because it was designed to be visually clear, technically accessible, and easy to operate through smartphones.

The language validation score increased from 62.50% to 86.60%, with an improvement of 24.10%. This indicates that revisions in wording, sentence clarity, readability, and appropriateness for tenth-grade students successfully improved the communicative quality of the media. In instructional media, language clarity is essential because students need to understand instructions, descriptions, and conceptual explanations without unnecessary ambiguity. The improvement in language validation suggests that the final version of the flashcards became more understandable and suitable for classroom use.

Overall, the expert validation results confirm that the augmented reality-assisted flashcards were feasible for implementation. The high feasibility score after revision shows that the product had met the minimum requirements of instructional quality from media, material, and language perspectives. These results also indicate that the ADDIE development process was effective in guiding systematic product refinement.

Students' Conceptual Mastery

The effectiveness of the augmented reality-assisted flashcards was examined by comparing students' pre-test and post-test scores in the experimental and control classes. The experimental class consisted of 35 students who learned using the developed AR-assisted flashcards, while the control class consisted of 35 students who learned through conventional instruction. Students' conceptual mastery was measured before and after the intervention.

Table 2. Students' Conceptual Mastery Test Results

Class	Number of Students	Mean Pre-test Score	Mean Post-test Score	N-Gain	Category
Control class	35	40.85	72.85	0.50	Moderate
Experimental class	35	39.14	89.71	0.82	High

As shown in Table 2, both the experimental and control classes experienced improvement after the learning process. The control class increased from a mean pre-test score of 40.85 to a mean post-test score of 72.85, with an N-Gain score of 0.50 in the moderate category. Meanwhile, the experimental class increased from a mean pre-test score of 39.14 to a mean post-test score of 89.71, with an N-Gain score of 0.82 in the high category. These results indicate that students who learned using augmented reality-assisted flashcards achieved greater improvement in conceptual mastery than students who learned through conventional instruction.

The difference between the two classes is pedagogically meaningful because the experimental class began with a slightly lower mean pre-test score than the control class. However, after the intervention, the experimental class achieved a substantially higher mean post-test score. This pattern suggests that the developed media provided a more effective learning experience for helping students understand ecosystem components and interactions. The N-Gain score of 0.82 indicates that the improvement in the experimental class was not merely incremental but reached a high level of learning gain.

The independent-samples t-test showed a significance value of 0.000. In academic reporting, this result should be written as $p < .001$ rather than $p = 0.000$, because probability values are not truly zero. The result indicates that there was a statistically significant difference between the experimental and control classes after the intervention. Therefore, the use of augmented reality-assisted flashcards had a significant effect on students' conceptual mastery of ecosystem components and interactions.

Discussion

The findings of this study demonstrate that augmented reality-assisted flashcards are feasible and effective as instructional media for biology learning. The feasibility of the product was supported by expert validation results, while its effectiveness was demonstrated by the higher N-Gain score and post-test achievement in the experimental class. These findings indicate that the developed media can serve as an innovative learning tool that supports students' understanding of abstract biological concepts through interactive visualization.

The improvement in expert validation scores reflects the importance of iterative development in instructional media design. The ADDIE model enabled the researchers to identify learning needs, design the product, develop the prototype, revise the media based on expert input, implement the product in classroom learning, and evaluate its effectiveness. This systematic process helped ensure that the final product was not only visually attractive but also pedagogically appropriate and conceptually accurate. In research and development studies, validation is not a mere administrative step; it is a quality assurance mechanism that strengthens the reliability of the developed product before it is used by students.

The highest improvement in material validation suggests that content refinement was one of the most important aspects of the development process. Biology learning requires conceptual precision because students often construct understanding based on the representations provided in learning media. If the representation is incomplete, confusing, or scientifically inaccurate, students may develop misconceptions. Therefore, the revision of content, learning objectives, examples, and conceptual descriptions was essential in ensuring that the media could support valid conceptual mastery. The final validation score of 89.16% from material experts indicates that the developed media was highly appropriate for the selected biology topic.

The improvement in media validation also shows that the integration of AR technology with printed flashcards was successfully refined. The strength of AR-assisted flashcards lies in their ability to combine simple physical media with interactive digital objects. This hybrid design makes the media practical and accessible because students can use printed cards while exploring 3D objects through their smartphones. In the context of school learning, this is important because technology-based media should be easy to use, not overly dependent on sophisticated infrastructure, and suitable for classroom conditions. By using Assemblr Edu, the media could present interactive AR objects without requiring complex programming or expensive equipment.

The improvement in language validation further confirms that readability and clarity are important in instructional media. Even when media contain attractive visuals and advanced technology, unclear language may reduce their instructional effectiveness. Students need concise, understandable, and age-appropriate explanations to connect visual representations with scientific concepts. The increase in language validation score indicates that the final version of the media became more communicative and suitable for tenth-grade students.

The effectiveness results provide strong evidence that augmented reality-assisted flashcards can improve students' conceptual mastery. The experimental class achieved an N-Gain score of 0.82, categorized as high, while the control class achieved an N-Gain score of 0.50, categorized as moderate. This difference suggests that AR-assisted flashcards provided additional learning support that was not available in conventional instruction. The three-dimensional visualization enabled students to observe ecosystem elements more concretely, helping them understand relationships among biotic components, abiotic components, and ecological interactions.

The topic of ecosystem components and interactions is inherently systemic (Loreau, 2010; Verma et al., 2025). Students must understand that organisms do not exist independently but interact with other organisms and environmental factors. They must also understand how energy flows, how food chains are structured, and how ecological balance is maintained. Such concepts are difficult to master through memorization alone. AR-assisted flashcards can support understanding because they present ecological objects and relationships in a more concrete, visual, and interactive form. Students can connect terms and definitions on the flashcards with 3D visualizations, making the learning experience more meaningful.

From a cognitive perspective, the effectiveness of AR-assisted flashcards may be explained by their ability to provide multimodal representations. Students receive information through text, images, and interactive 3D objects. These multiple representations can help students organize information and build stronger conceptual links. When students observe a 3D object related to the concept being studied, they are more likely to develop a mental representation that is richer than one formed only through verbal explanation. This may explain why the experimental class demonstrated higher improvement than the control class.

The findings also suggest that AR-assisted flashcards can increase students' engagement in biology learning. Although this study focused primarily on conceptual mastery, the use of interactive media likely created a more attractive and exploratory learning environment. Students could interact with the media directly, observe objects from different perspectives, and discuss what they observed with peers. This type of learning experience can encourage active participation and reduce the monotony often associated with conventional instruction. In science learning, engagement is important because students who are actively involved are more likely to ask questions, make observations, and construct explanations.

In practical terms, the developed media offers a useful alternative for biology teachers. Many schools have limitations in laboratory equipment, biological specimens, or time for outdoor observation. AR-assisted flashcards can help overcome some of these limitations by providing digital representations of biological objects and ecological interactions. The media can be used in classroom discussions, group activities, individual learning, or enrichment tasks. Its compatibility with smartphones also makes it relevant to students' everyday digital practices. Thus, the media does not simply introduce technology into the classroom; it transforms technology into a pedagogical tool for conceptual learning.

The novelty of this study lies in the development of AR-assisted flashcards specifically for tenth-grade biology learning on ecosystem components and interactions. While AR has been widely discussed in educational technology research, its integration with hardcard-based flashcards for senior high school biology remains an area that requires further exploration. This study contributes by demonstrating that a relatively simple and accessible AR-based medium can produce meaningful improvement in students' conceptual mastery. The product also provides a model for how teachers and researchers can combine low-cost printed media with digital technology.

Nevertheless, several limitations should be acknowledged. First, the implementation was conducted in one school and involved only one biology topic. Therefore, the findings cannot be generalized to all biology topics or educational contexts without further investigation. Second, the study measured students' conceptual mastery immediately after the intervention, so it did not examine long-term retention. Future studies should investigate whether students retain their conceptual understanding after several weeks or months. Third, the reported statistical analysis was limited to N-Gain and significance testing. To strengthen future findings, researchers should include additional statistical information such as standard deviation, t-value, degrees of freedom, confidence interval, and effect size.

Despite these limitations, the results indicate that augmented reality-assisted flashcards have strong potential as an innovative instructional medium in biology education. The media was validated as highly feasible by experts and demonstrated a significant effect on students' conceptual mastery. The integration of printed flashcards and AR technology provides an effective bridge between conventional learning materials and digital interactivity. Therefore, this study supports the use of AR-assisted flashcards as a practical and pedagogically meaningful innovation for improving biology learning in the digital era.

CONCLUSION

This study developed augmented reality-assisted flashcards using the ADDIE model and examined their feasibility and effectiveness in improving tenth-grade students' conceptual mastery of ecosystem components and interactions. The development process involved systematic stages of needs analysis, instructional design, prototype development, expert validation, classroom implementation, and evaluation. The validation results indicated that the developed media was highly feasible, as reflected in the scores obtained from media experts, material experts, and language experts, all of which exceeded 85% after revision. The effectiveness test further demonstrated that students who learned using augmented reality-assisted flashcards achieved greater improvement in conceptual mastery than those who received conventional instruction, with the experimental class obtaining a high N-Gain score of 0.82 compared with 0.50 in the control class. The independent-samples t-test also showed a statistically significant difference between the two groups, indicating that the developed media had a positive effect on students' conceptual mastery. These findings suggest that the integration of printed flashcards with three-dimensional augmented reality visualization can provide a more interactive, concrete, and engaging learning experience for biology students. The media is particularly useful for helping students understand abstract ecological concepts by connecting textual information, visual representation, and digital interaction. Therefore, augmented reality-assisted flashcards can be considered a feasible and effective instructional innovation for biology learning in senior high school. Nevertheless, this study was limited to one school, one grade level, and one biology topic; therefore, future research is recommended to examine the use of similar media across different biological concepts, broader student populations, and longer implementation periods to evaluate its impact on long-term retention and conceptual transfer.

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