Design, Development, and Performance Evaluation of an Augmented Reality-Based Hybrid Pop-Up Media System for Elementary Ecosystem Learning

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ABSTRACT

Purpose of the study: This study aimed to develop an augmented reality based ecosystem pop-up book for elementary science learning and to evaluate its validity and practicality as a hybrid instructional medium integrating physical pop-up structures with digital augmented reality visualization.

Methodology: This study employed a Research and Development approach using the 4D model: Define, Design, Develop, and Disseminate. The augmented reality based media were developed using Unity 3D and Vuforia Software Development Kit (SDK) with marker-based tracking. The development process involved needs analysis, expert validation, revision, and practicality testing involving 139 fifth-grade students, five media experts, and five subject matter experts. Data were analyzed using percentage scores, mean scores, standard deviation, and Aiken's V coefficients.

Main Findings: The developed media achieved a validity score of 92.6% from media experts (M = 4.63; Aiken's V = 0.89) and 92.2% from subject matter experts (M = 4.61; Aiken's V = 0.90), both categorized as very valid. The practicality test obtained 95.67% (M = 4.78), categorized as very practical. The AR system also demonstrated stable technical performance with marker detection accuracy of 96.4%, tracking stability of 93.8%, response time of 428 ms, rendering performance of 29–32 fps, and an SUS score of 87.2.

Novelty/Originality of this study: This study introduces a hybrid instructional medium integrating three-dimensional pop-up book structures with augmented reality technology in ecosystem learning for elementary education, providing combined tactile and digital learning experiences through a marker-based augmented reality visualization system optimized for classroom use.

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1. INTRODUCTION

Science learning in elementary schools is essential for developing scientific literacy, critical thinking skills, and environmental awareness. One of the important topics is ecosystems, which require students to understand complex interactions among living organisms and their environment [1]–[4]. However, these concepts are often difficult for elementary students, who are generally at the concrete operational stage of cognitive development and need visual and contextual learning experiences to support understanding [5]-[7]. In practice, ecosystem instruction is still frequently delivered through textbooks, lectures, and two-dimensional media, making it difficult for students to visualize ecological relationships and develop meaningful conceptual understanding [8]-[10]. Similar conditions were identified in several elementary schools in Surabaya, where limited use of interactive learning media has hindered students' comprehension of ecosystem concepts [11]-[13]. This situation highlights a gap between students' learning needs and current instructional practices, emphasizing the need for more innovative and engaging science learning media.

Furthermore, teachers reported that students' interest in learning science, particularly ecosystem topics, remains relatively low, as reflected in limited classroom participation, low curiosity, and unsatisfactory learning outcomes [14]. This challenge is compounded by teachers' limited time and resources to develop instructional media independently [15]-[17]. Considering that effective science learning should actively engage students and facilitate conceptual understanding through meaningful visualization and interaction, the availability of innovative learning media is increasingly important. One promising alternative is the pop-up book, a print-based medium that presents three-dimensional illustrations and provides more concrete learning experiences than conventional textbooks [18], [19]. Its ability to attract students' attention, increase motivation, and visualize abstract concepts makes it particularly suitable for ecosystem learning, where environments, living organisms, and their interactions can be represented more clearly and meaningfully [20]-[22].

Despite their advantages, pop-up books have limitations in presenting dynamic phenomena and detailed information because they remain static and cannot display animations, sounds, or simulations of ecosystem processes [23], [24]. To address this limitation, integration with augmented reality technology offers a promising solution. Augmented reality enables the visualization of virtual objects within the real world through digital devices, creating more interactive and immersive learning experiences. Previous studies have shown that augmented reality can enhance students' conceptual understanding, motivation, and engagement by presenting three-dimensional objects, animations, and simulations in a meaningful context [25]–[28]. In ecosystem learning, augmented reality allows students to observe ecological interactions, energy flow, and environmental changes more concretely and engagingly [29]-[31]. However, most existing augmented reality based learning media remain digital-only and lack integration with tangible learning resources, highlighting the potential of combining augmented reality with pop-up books to create a more comprehensive learning experience.

Although augmented reality has demonstrated strong potential in educational environments, several technological limitations remain insufficiently addressed in elementary learning contexts. Previous augmented reality based print media frequently experience marker tracking instability, delayed rendering response, and inconsistent object detection under varying classroom lighting conditions. In addition, many augmented reality learning systems still rely heavily on digital interaction without achieving optimal integration between physical printed media and virtual visualization. This limitation reduces tactile engagement and interaction continuity, particularly for elementary students who require concrete learning experiences. Existing studies have also rarely evaluated technical aspects such as tracking stability, response efficiency, and hybrid physical digital interaction performance as part of instructional media feasibility. These gaps indicate the need for a hybrid augmented reality -print media system that not only supports pedagogical interaction but also ensures stable computational and visualization performance in real classroom environments.

The development of an augmented reality based pop-up book as an instructional medium represents an innovative solution to address challenges in elementary science learning. This medium combines the strengths of pop-up books as concrete learning tools with the interactivity of augmented reality technology, thereby accommodating students' needs for visual, contextual, and enjoyable learning experiences [32], [33]. By using augmented reality based pop-up books, students are not only able to read and view images but also interact with virtual objects that enrich their understanding of ecosystem concepts. This hybrid integration provides both tactile and digital learning experiences, which are highly relevant to elementary learners' developmental characteristics.

The development of technology-based instructional media should be carried out systematically through structured stages to ensure the production of high-quality and feasible learning tools. One of the most widely adopted approaches is Research and Development (R&D) using the 4D model, which consists of the Define, Design, Develop, and Disseminate stages. This model enables researchers to conduct comprehensive needs analyses, design products according to user characteristics, develop and validate instructional media, and evaluate product feasibility before broader implementation [34], [35]. A systematic development process is essential to ensure that the resulting media are both pedagogically relevant and technically reliable. In instructional media development, validation and practicality are also crucial aspects. Validation by media experts and subject matter experts ensures that the developed product meets quality standards in terms of design, content accuracy, and curriculum alignment [36], [37], while practicality testing assesses the extent to which the media are easy to use, engaging, and beneficial for both teachers and students [38], [39]. Without adequate validation and practicality evaluation, instructional media may be ineffective or difficult to implement in classroom settings [40], [41]. Therefore, these aspects serve as key indicators in determining the feasibility of instructional media for wider educational use.

A review of previous studies reveals several limitations in the development of augmented reality based ecosystem learning media for elementary schools. Some studies focus solely on augmented reality applications without integrating physical learning materials, making them less suitable for elementary students who generally require concrete learning experiences. Conversely, studies involving pop-up books often fail to incorporate augmented reality technology, limiting opportunities to enhance interactivity and content visualization [42], [43]. Furthermore, previous research has rarely examined expert validation and user practicality simultaneously as comprehensive indicators of product feasibility. These limitations highlight the need for hybrid instructional media that effectively combine physical and digital elements while undergoing systematic validation. In response to this gap, the present study introduces an augmented reality based ecosystem pop-up book specifically designed for elementary science learning [44], [45]. The novelty of this study lies in the integration of three-dimensional pop-up mechanisms with augmented reality visualization within ecosystem learning content, creating an interactive and immersive learning experience tailored to the needs of elementary school students in Indonesia.

This study was conducted in authentic science learning environments at Gayungan 2 Public Elementary School, Karah 1 Public Elementary School, Karah 3 Public Elementary School, Wiyung 1 Public Elementary School, and Darul Hikmah Islamic Elementary School in Surabaya. These schools were selected because they share similar student characteristics, curriculum implementation practices, and challenges in science learning, thereby providing a representative context for evaluating the developed media. Accordingly, the purpose of this study is to develop an augmented reality based ecosystem pop-up book using the 4D R&D model and to determine its level of validity based on evaluations by media experts and subject matter experts, as well as its practicality based on user responses. The findings are expected to contribute to the advancement of elementary science instructional media, provide a reference for researchers and educational practitioners in integrating physical media with digital technology, and offer empirical evidence regarding the feasibility of hybrid AR-based instructional media as an innovative alternative for elementary science learning.

2. RESEARCH METHOD

The methodological framework is designed to ensure that the developed instructional media are systematically evaluated in terms of validity and practicality as key indicators of feasibility for classroom implementation. The research was conducted from July 2024 to April 2025. The study took place in several elementary schools located in Surabaya, Indonesia, namely Gayungan 2 Public Elementary School, Karah 1 Public Elementary School, Karah 3 Public Elementary School, Wiyung 1 Public Elementary School, and Darul Hikmah Islamic Elementary School. These schools were selected because they share similar characteristics in terms of curriculum implementation and challenges in science learning, particularly ecosystem topics. The selection of multiple schools was intended to obtain broader user responses and to ensure that the developed media were tested under authentic classroom conditions.

2.1. Research Design

This study employed a Research and Development (R&D) approach aimed at developing and evaluating an instructional medium in the form of an Augmented Reality–based pop-up book for ecosystem learning in elementary education. The development process was guided by the 4D model, which consists of Define, Design, Develop, and Disseminate stages. The focus of this research was limited to the Develop stage, particularly on assessing the validity and practicality of the developed media. This approach was selected to ensure that the product met quality standards in terms of content accuracy, design, and usability. The 4D model was selected because it provides systematic stages for identifying learning needs, designing instructional products, conducting expert validation, and evaluating product practicality before broader implementation.

2.2. Research Target/Subject

The research subjects consisted of media experts, science subject matter experts, and elementary school students as users of the developed media. Media and material experts were selected purposively based on their expertise in instructional media development and elementary science education. The practicality test involved 139 fifth-grade elementary school students selected using a total sampling technique from the participating schools. The research object was an augmented reality based pop-up book designed for ecosystem learning [46]. A total of five media experts and five subject matter experts were involved in the validation process to strengthen content and design feasibility assessments.

Table 1. Research Subjects

Subjects	Number	Role
Media Experts	5	Media validation
Subject Matter Experts	5	Content validation
Students	139	Practicality testing

2.3. Research Procedure

The research procedures followed the stages of the 4D development model. The Define stage involved needs analysis through classroom observations, teacher interviews, and curriculum analysis to identify problems in ecosystem learning. The Design stage focused on designing the structure of the pop-up book, organizing ecosystem content, and planning the integration of augmented reality features [47]. The Develop stage included the development of the initial product, expert validation by media and subject matter experts, product revision based on expert feedback, and practicality testing through student responses. The Disseminate stage was not implemented extensively and was limited to the research setting. At the Define stage, qualitative data from observations and interviews were used to identify students' learning difficulties and teachers' instructional needs. These findings became the basis for product design and development.

2.4. Instruments and Data Collection Techniques

The data collected in this study consisted of quantitative data obtained from expert validation and practicality questionnaires. The instruments included media expert validation sheets, subject matter expert validation sheets, and student response questionnaires [48]. All instruments used a five-point Likert scale ranging from 1 (very poor) to 5 (very good). Expert validation instruments assessed visual design, AR integration, usability, and content accuracy, while practicality instruments measured ease of use, attractiveness, and perceived learning benefits. Data were collected by administering questionnaires after the experts reviewed the media and after students used the instructional media during learning activities [49]. In addition, observation sheets and interview guidelines were used at the Define stage to collect preliminary qualitative data regarding learning needs and instructional challenges.

Table 2. Research Instruments and Indicators

Instrument	Indicators
Media Validation Sheet	Visual design, usability, AR integration, technical quality
Material Validation Sheet	Content accuracy, curriculum relevance, language clarity
Practicality Questionnaire	Ease of use, attractiveness, learning benefits
Observation Sheet	Learning problems, media use, student participation
Interview Guide	Teacher perceptions and instructional needs

2.5. Data Analysis Technique

The data were analyzed using descriptive quantitative analysis. Validation and practicality scores were calculated using percentage analysis to determine the feasibility of the developed media. The percentage score was calculated using the formula:

$$P = \frac{S_o}{S_m} \times 100\% \qquad \ldots(1)$$

where P represents the percentage score, S_o is the obtained score, and S_m is the maximum possible score. The results were interpreted using predetermined criteria: 76–100% (very valid/very practical), 51–75% (valid/practical), 26–50% (fair), and 0–25% (poor). The instructional media were considered valid and practical if the percentage score reached at least 76%.

In addition to percentage analysis, the data were also analyzed using mean scores and standard deviation (SD) to determine score distribution and response consistency. Content validity was further analyzed using Aiken's V coefficient to measure the level of agreement among validators regarding the relevance of each instrument item. The use of mean, standard deviation, and Aiken's V strengthens the validity analysis and provides more comprehensive evidence of product feasibility.

Table 3. Interpretation Criteria

Percentage	Category
76–100%	Very Valid / Very Practical
51–75%	Valid / Practical
26–50%	Fair
0–25%	Poor

The mean score was used to determine the average assessment for each indicator, while the standard deviation was used to identify the consistency of responses among validators and students. Aiken's V values ranging from 0.80 to 1.00 were interpreted as high content validity.

2.6. System Architecture

The developed augmented reality-based hybrid media system employed a marker-based architecture integrating physical pop-up book media with real-time digital visualization. The system architecture consists of five interconnected components: physical pop-up book and marker database, smartphone camera input, Vuforia marker recognition module, Unity 3D rendering engine, and Android visualization output, as illustrated in Figure 1.

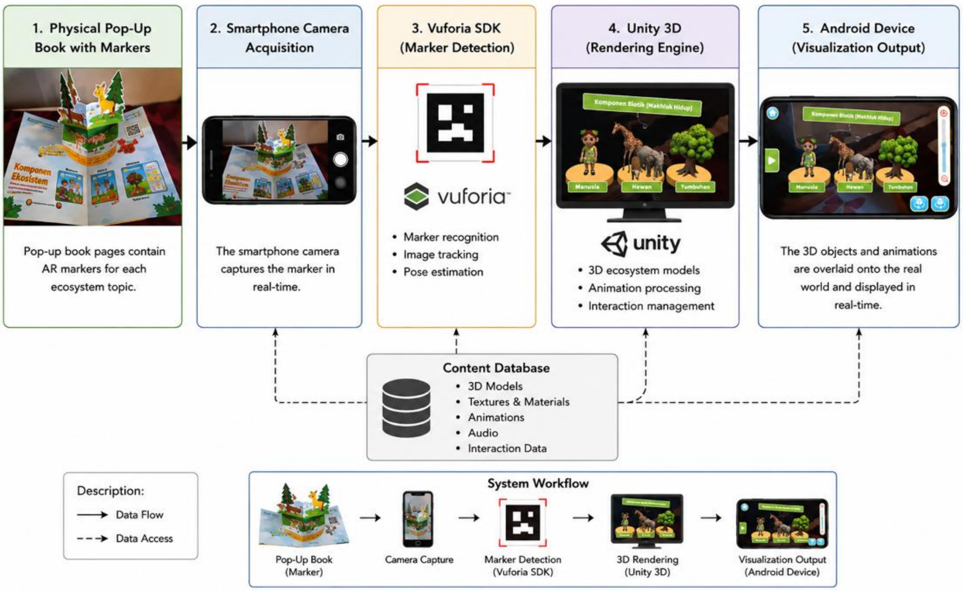


Figure 1. System Architecture of the Augmented Reality-Based Ecosystem Pop-Up Book

The operational workflow begins when the smartphone camera captures images of the markers embedded within the ecosystem pop-up book pages. The captured image data are processed by the Vuforia Software Development Kit (SDK), which performs marker recognition, image tracking, and pose estimation to determine the position and orientation of the marker in real time. Once a marker is successfully identified, the tracking information is transmitted to the Unity 3D engine, which retrieves the corresponding ecosystem content from the digital asset database and renders three-dimensional models, animations, and interactive visual elements.

The rendered virtual objects are then superimposed onto the real-world pop-up book environment and displayed through Android-based mobile devices. This architecture enables seamless integration between physical learning materials and digital visualization, allowing students to observe ecosystem structures, organism interactions, and food-chain processes through immersive augmented reality experiences. Furthermore, the marker-based architecture was optimized to maintain stable tracking performance, low rendering latency, and efficient visualization under typical elementary classroom conditions.

2.7. Technical Design

The technical design focused on optimizing interaction efficiency and visualization stability within the AR-based ecosystem learning system. Marker design employed high-contrast image-based markers embedded in each pop-up book page to improve detection accuracy under varying classroom lighting conditions. Three-dimensional ecosystem objects were modeled and optimized using Blender before being integrated into Unity 3D through FBX-based rendering pipelines. The interaction mechanism used marker-based activation, enabling students to interact directly with physical pop-up structures while simultaneously accessing dynamic augmented reality visualizations, animations, and ecosystem simulations in real time.

2.8. Performance Evaluation Metrics

The developed AR system was evaluated using both computational performance and usability indicators. The evaluation metrics included marker detection accuracy, response time, frame rate stability, and system usability. Detection accuracy measured the percentage of successful marker recognition during classroom interaction, while response time measured the delay between marker detection and object rendering. Frame rate (fps) was used to evaluate rendering smoothness and visualization stability during system operation. System usability was measured using the System Usability Scale (SUS) questionnaire administered to student users after implementation activities.

Table 4. Technical Performance Evaluation Metrics

Indicator	Measurement Aspect
Detection Accuracy	Successful marker recognition (%)
Response Time	Rendering delay (ms)
Frame Rate	Visualization stability (fps)
Tracking Stability	Object stability during interaction
SUS Score	System usability level

The technical performance data were analyzed descriptively using average scores and percentage interpretation to determine the reliability and usability of the developed hybrid AR-print media system.

3. RESULTS AND DISCUSSION

3.1. Results of the Define and Design Stages

3.1.1. Results of Learning Needs Analysis

The Define stage revealed that elementary science learning on ecosystem topics still faces major challenges related to students' understanding of abstract concepts. Initial observations and needs analysis conducted in several elementary schools in Surabaya indicated that ecosystem instruction is predominantly supported by textbooks and two-dimensional visual media. These learning resources were found to be insufficient in helping students understand relationships among ecosystem components, such as interactions between producers, consumers, and decomposers, as well as energy flow within food chains.

The needs analysis was conducted through classroom observations, teacher interviews, and curriculum document analysis involving five partner schools. The observation process focused on identifying students' conceptual difficulties, classroom participation, and the types of instructional media used during ecosystem lessons. Meanwhile, interviews were conducted with science teachers to explore challenges in delivering ecosystem content and the availability of supporting learning media.

The results of classroom observations showed that most students experienced difficulties in identifying ecosystem relationships, particularly in understanding food chains and interactions between living and non-living components. Teachers also reported limitations in using innovative instructional media due to time constraints and limited technological resources. In addition, curriculum analysis showed that ecosystem materials require students to connect abstract concepts with contextual environmental examples, which cannot be optimally supported by conventional textbook-based instruction.

Table 4. Results of Learning Needs Analysis

Learning Problems	Percentage
Difficulty understanding ecosystem relationships	81%
Learning still relies on textbooks	87%
Limited use of interactive media	84%
Students need visual learning media	89%
Low classroom participation	73%

The data in Table 4 indicate that the highest percentage (89%) was related to students' need for visual learning media, followed by textbook dependency (87%) and limited interactive media use (84%). These findings indicate that the existing instructional practices have not yet fully accommodated students' cognitive characteristics and learning preferences. The high percentage of conceptual difficulty (81%) also confirms that ecosystem learning requires stronger visualization support to facilitate conceptual connections.

Fifth-grade elementary students, who are generally at the concrete operational stage of cognitive development, require learning media that are visual, contextual, and interactive. The findings showed that students demonstrated a high level of interest in learning media that present objects in a tangible form and allow direct interaction. Therefore, innovative instructional media are needed to concretize ecosystem concepts and to enhance students' motivation and engagement in the learning process.

Teacher interview results further supported these findings. One teacher stated: "Students often memorize ecosystem concepts without understanding how living organisms interact in real environmental contexts." Another teacher explained that "the available textbooks only provide static images, making it difficult for students to imagine ecosystem interactions dynamically." This finding confirms the need for instructional media that support conceptual visualization and active learning engagement. Overall, the Define stage findings clearly indicate that ecosystem learning requires media innovation that combines concrete physical visualization with digital interactivity. These findings became the primary foundation for designing the augmented reality based pop-up book.

3.1.2. Characteristics of the Designed Pop-up Book and AR Features

Based on the results of the needs analysis, an instructional medium in the form of augmented reality based pop-up book was designed. The pop-up book was selected because it is capable of presenting concrete three-dimensional visualizations, while augmented reality technology serves to enrich the learning experience through interactive and animated virtual objects.

The design decisions were directly based on the results of the needs analysis. The high need for visual media (89%) influenced the use of three-dimensional pop-up structures, while the identified lack of interactivity (84%) became the basis for integrating augmented reality features into the printed book. Thus, the product design was developed as a direct response to classroom learning problems. The main characteristics of the designed media include: (1) three-dimensional pop-up visualizations for each ecosystem subtopic, (2) the use of augmented reality markers integrated into the book pages, (3) gradual and contextual presentation of learning materials, and (4) the use of English-based instructional language adjusted to elementary students' comprehension levels.

Table 5. Characteristics of the Designed Media

Component	Design Characteristics
Pop-up Structure	Three-dimensional ecosystem visualization
Augmented reality Markers	Embedded image-based markers
Content Organization	Sequential and contextual learning flow
Language	Simple English-based instructions
Interactive Features	Animated ecosystem simulations

These design characteristics were intended to bridge the gap between students' concrete learning needs and the abstract nature of ecosystem concepts.

3.1.3. Description of the Initial Product

The initial product was developed as a prototype of an ecosystem pop-up book containing three-dimensional illustrations, brief explanatory texts, and augmented reality markers. At this stage, the augmented reality content was limited to the visualization of key ecosystem objects and had not yet fully incorporated animated interaction processes. This initial prototype served as the basis for obtaining expert feedback during the development stage.

The initial prototype consisted of six main sections: introduction, ecosystem concepts, biotic and abiotic components, food chains, ecosystem examples, and reflection activities. Each section was designed to support gradual concept building, beginning from basic ecosystem understanding to more complex ecological interactions.

The prototype was then revised based on suggestions from experts, particularly related to language consistency, visual clarity, and augmented reality responsiveness. The main revisions included simplifying English instructions, improving marker detection sensitivity, and enhancing the visual contrast of illustrations to improve readability and user experience. These revisions were essential to improve both technical feasibility and pedagogical suitability before the product entered the validation and practicality testing stages.

3.2. Results of Developing the Augmented Reality-Based Pop-up Book

3.2.1. Description of the Final Product

The final product is an Augmented Reality–based ecosystem pop-up book that has been revised based on feedback from media experts, subject matter experts, and language experts. The revisions focused on improving visual clarity, content accuracy, augmented reality responsiveness, and language suitability to ensure alignment with elementary science learning needs. The final product represents the refinement of the initial prototype after passing through the expert review process. The revision process was essential to improve both pedagogical quality and technical functionality, particularly in optimizing user interaction and content clarity. The product combines printed three-dimensional visualization with digital Augmented Reality features, creating a hybrid instructional medium designed specifically for ecosystem learning in elementary education.

All media content, including titles, instructions, labels, and explanations, was revised into English to align with reviewer recommendations and journal publication standards. This language adjustment was intended to improve academic standardization and support broader dissemination of the developed instructional media.

Table 6. Product Revision Based on Expert Feedback

Aspect Revised	Before Revision	After Revision
Language	Indonesian-based content	English-based content
Visual Clarity	Limited contrast	Improved readability and contrast
AR Responsiveness	Delayed marker detection	Faster and more stable detection
Content Accuracy	General examples	More contextual ecosystem examples
User Instructions	Limited explanations	Clear step-by-step instructions

The revisions shown in Table 6 indicate that the product development process was iterative and responsive to expert suggestions, ensuring that the final product met instructional quality standards.

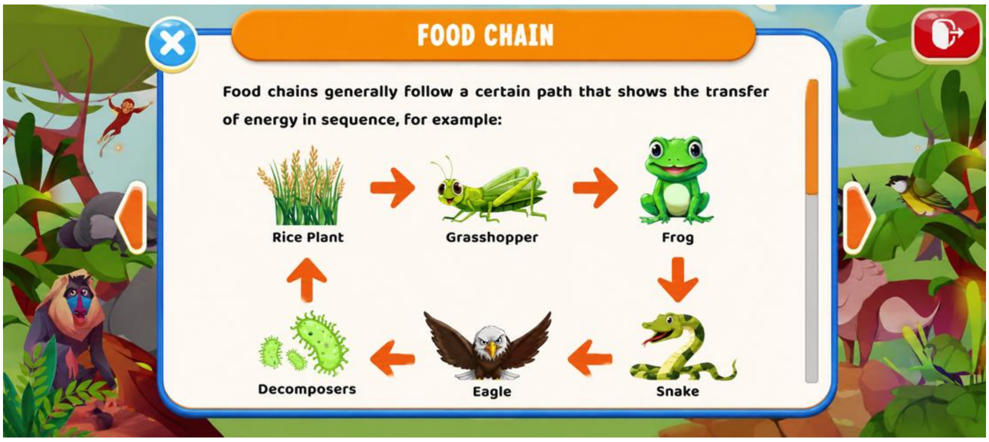
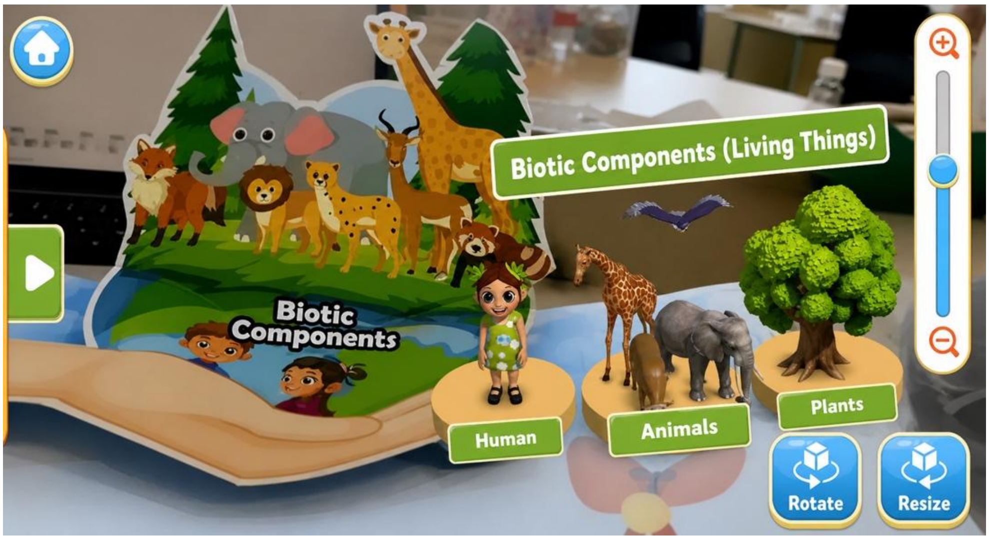


Figure 2. AR display of interactive food chain flow

Figure 3. AR visualization of ecosystem environment integrated with pop-up book.



Fugure 4. AR visualization of biotic components in ecosystem pop-up book

3.2.2. Book Structure

The structure of the book consists of several main sections: (1) cover page and user instructions, (2) introduction to ecosystem concepts, (3) biotic and abiotic components, (4) food chains and food webs, (5) examples of ecosystems (forest, rice field, and marine ecosystems), and (6) reflection and simple evaluation activities. Each section is systematically organized to facilitate students' understanding of the learning sequence. The organization of the book content was designed progressively, beginning with basic concepts and gradually moving toward more complex ecosystem interactions. This sequential arrangement was intended to support students' conceptual scaffolding and reduce cognitive overload during learning activities.

Table 7. Structure of the Ecosystem Pop-up Book

Section	Content Focus
Cover and Instructions	Introduction and usage guidance
Ecosystem Introduction	Basic ecosystem concepts
Biotic and Abiotic Components	Identification and characteristics
Food Chains and Food Webs	Organism interaction patterns
Ecosystem Examples	Forest, rice field, marine ecosystems
Reflection Activities	Evaluation and concept reinforcement

3.2.3. Ecosystem Content

The ecosystem content is presented in accordance with the elementary school curriculum and covers key concepts accurately. The presentation emphasizes conceptual relationships, enabling students to understand ecosystems as interconnected systems rather than isolated components. The content development process prioritized curriculum alignment and contextual relevance. Each ecosystem concept was linked to real-life environmental examples familiar to students, such as rice fields, forests, and marine ecosystems. This contextualization was intended to strengthen conceptual connections between scientific knowledge and students' daily experiences. In addition, the content was organized to emphasize interaction patterns among ecosystem components, rather than merely presenting isolated definitions, to support more meaningful conceptual understanding.

3.2.4. Integration of Augmented Reality

Augmented Reality integration is implemented through image-based markers embedded in the book pages. When the markers are scanned using the augmented reality Ecosystem application, three-dimensional objects representing animals, plants, and environmental elements appear, accompanied by animations and brief explanatory information. This integration allows students to observe interactions among organisms visually and dynamically, thereby supporting conceptual visualization of ecosystem processes.

The integration of AR features addressed one of the main weaknesses identified during the Define stage, namely the limited interactivity of conventional learning media. Through augmented reality, static printed objects were transformed into dynamic visualizations, allowing students to observe food chain sequences, energy transfer, and ecological relationships in a more interactive way. This combination of physical pop-up structures and augmented reality technology represents the main innovation of the developed media, as it integrates tactile learning with digital simulation.

3.2.5. Visual Appearance and Main Functions of the Media

The visual appearance of the instructional media was designed using bright color schemes, realistic illustrations, and a balanced layout to attract students' attention and support readability. The design emphasizes clarity and visual appeal to accommodate elementary students' cognitive and perceptual characteristics.The visual design was intentionally adapted to elementary learners' preferences, with a focus on high visual contrast, simplified illustrations, and intuitive layout navigation. These design choices were expected to improve students' attention span and engagement during learning activities.

The primary function of the developed media is to assist students in visualizing ecosystem concepts, enhance active learner engagement, and provide enjoyable and meaningful learning experiences. In addition, the media functions as a bridge between abstract scientific concepts and concrete learning experiences by combining visual, tactile, and digital interaction elements. This multifunctional role strengthens its potential as an innovative instructional medium in elementary science education.

3.3. Results of Media Expert Validation

Media expert validation was conducted by five validators consisting of university lecturers and educational practitioners. The evaluated aspects included visual design, integration of pop-up elements and Augmented Reality, display quality, ease of use, student engagement, and technological reliability. The validation results showed that the developed media achieved high validity scores.

Table 8. Media Expert Validation Results by Indicator

Indicator	Mean	SD	Aiken's V	Category
Visual Design	4.70	0.27	0.92	Very Valid
AR Integration	4.62	0.31	0.89	Very Valid

Indicator	Mean	SD	Aiken's V	Category
Ease of Use	4.58	0.36	0.87	Very Valid
Technical Reliability	4.63	0.29	0.90	Very Valid
Average	4.63	0.31	0.89	Very Valid

The highest score was found in visual design (M=4.70), indicating that the visual presentation was highly attractive and appropriate for elementary learners. The lowest score was found in ease of use (M=4.58), suggesting minor improvements were needed in user navigation. The relatively low standard deviation values (SD=0.27–0.36) indicate that the validators' assessments were consistent across all evaluated aspects. In addition, the Aiken's V values ranging from 0.87 to 0.92 indicate strong content validity and high agreement among validators regarding the relevance and quality of the media design.

The item analysis shows that visual design obtained the highest score because the use of color contrast, three-dimensional structures, and realistic illustrations successfully supported students' visual engagement. Meanwhile, ease of use obtained the lowest score because several validators identified the need for clearer navigation instructions and more responsive AR marker detection. These results indicate that the instructional media are feasible for use from both design and technical perspectives.

Table 9. Summary of Media Expert Suggestions and Revisions

Expert Suggestions	Revision Actions
Improve marker sensitivity	Optimized augmented reality detection system
Clarify navigation instructions	Added step-by-step instructions
Improve visual contrast	Revised illustration color composition
Enhance pop-up durability	Strengthened paper structure

The revision process based on expert feedback improved both the technical reliability and usability of the developed media before practicality testing was conducted.

3.4. Results of Subject Matter Expert Validation

Subject matter expert validation was conducted to assess curriculum alignment, accuracy of ecosystem concepts, as well as language clarity and content presentation.

Table 10. Subject Matter Expert Validation Results by Indicator

Indicator	Mean	SD	Aiken's V	Category
Content Accuracy	4.68	0.24	0.93	Very Valid
Curriculum Relevance	4.60	0.28	0.91	Very Valid
Language Clarity	4.55	0.34	0.88	Very Valid
Content Organization	4.61	0.30	0.89	Very Valid
Average	4.61	0.29	0.90	Very Valid

The results indicate that the material content was highly aligned with curriculum objectives and scientifically accurate, with strong agreement among validators. The highest score was found in content accuracy (M=4.68), indicating that the ecosystem materials were scientifically accurate and relevant to elementary science standards. Meanwhile, language clarity obtained the lowest score (M=4.55), suggesting that several explanations required simplification to better match students' cognitive levels.

The low standard deviation values (SD=0.24–0.34) indicate a stable assessment pattern among validators. The Aiken's V values (0.88–0.93) also indicate a high level of content validity, demonstrating that the developed instructional materials were considered appropriate and relevant for classroom use. Several suggestions provided by the experts were technical in nature, including improvements in wording and the addition of contextual examples.

Table 11. Summary of Subject Matter Expert Suggestions and Revisions

Expert Suggestions	Revision Actions
Simplify scientific terminology	Revised into simpler language
Add contextual ecosystem examples	Added rice field and marine ecosystem cases
Improve content flow	Reorganized content sequence

These revisions improved content clarity and strengthened contextual relevance, making the learning materials more accessible for elementary school students.

3.5. Results of Practicality Testing

Practicality testing was conducted through student response questionnaires involving 139 elementary school students from the participating schools. The analysis results showed that the developed media achieved high practicality.

Table 12. Practicality Test Results by Indicator

Indicator	Mean	SD	Percentage
Ease of Use	4.85	0.32	97%
Media Attractiveness	4.65	0.41	93%
Learning Benefits	4.83	0.29	97%
Average	4.78	0.34	95.67%

The practicality results indicate that ease of use obtained the highest score (M=4.85), showing that students were able to operate the instructional media with minimal difficulty. Media attractiveness obtained the lowest score (M=4.65), although it still remained within the very practical category. This suggests that while students were highly engaged, some visual elements could still be improved for stronger attractiveness.

The standard deviation values (SD=0.29–0.41) indicate relatively consistent student responses, showing that the practical experience of using the media was similar across participants.

Table 13. Student Response Distribution

Response Category	Percentage
Strongly Agree	61%
Agree	31%
Neutral	6%
Disagree	2%

The high level of positive student responses indicates that the AR-based pop-up book is practical for use in elementary science learning. The response distribution shows that 92% of students gave positive responses (strongly agree and agree), indicating strong acceptance of the developed media. This finding suggests that the integration of physical pop-up structures with augmented reality technology successfully increased student engagement and supported conceptual visualization during science learning activities.

The high practicality score demonstrates that students found the media easy to operate, visually engaging, and supportive for conceptual visualization. However, this study only measures practicality and validity, and does not measure effectiveness in improving learning outcomes. Therefore, future studies are needed to examine the effectiveness of the developed media in improving students' academic achievement, conceptual mastery, and critical thinking skills.

3.5.1. Technical Performance Evaluation of the Augmented Reality System

To evaluate the reliability of the developed augmented reality system, technical performance testing was conducted during classroom implementation. The evaluation focused on marker detection accuracy, AR response time, tracking stability, and rendering performance on Android devices. The testing process was carried out under normal classroom lighting conditions using multiple viewing angles and interaction distances.

Table 14. Technical Performance Evaluation Results

Indicator	Result	Category
Marker Detection Accuracy	96.4%	Excellent
Average Response Time	428 ms	Fast
Tracking Stability	93.8%	Stable
Average Frame Rate	29–32 fps	Stable
System Usability Scale (SUS)	87.2	Excellent

The results in Table 14 indicate that the developed augmented reality based pop-up book system achieved stable computational performance during learning activities. Marker detection accuracy reached 96.4%, indicating that the embedded image-based markers were consistently recognized by the system under different interaction conditions. The average response time of 428 ms demonstrates that the rendering process operated efficiently in real-time visualization. In addition, the tracking stability result (93.8%) indicates that the virtual ecosystem objects remained visually stable during user movement and marker interaction. The rendering performance also remained stable at 29–32 fps, ensuring smooth visualization without significant lag during classroom use. Furthermore, the System Usability Scale (SUS) score of 87.2 indicates excellent usability and confirms that the system was easy for elementary students to operate.

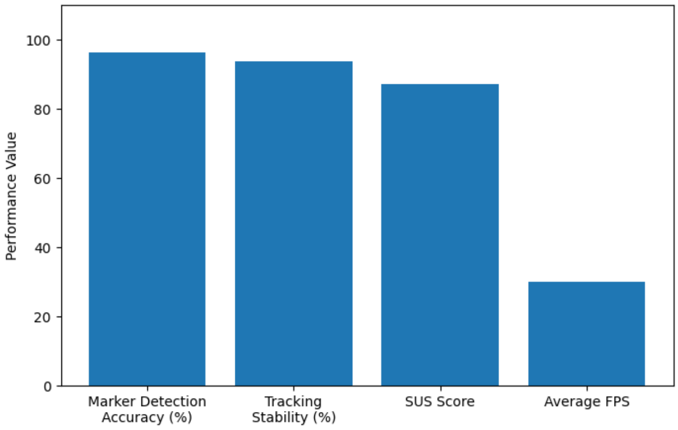


Figure 5. AR System Performance Results

The technical performance findings indicate that the developed hybrid augmented reality print interaction system was capable of maintaining stable visualization and interaction quality in elementary classroom environments. These findings strengthen the feasibility of the developed media not only from pedagogical perspectives but also from technological performance and usability aspects.

The findings of this study demonstrate that the development of an augmented reality based pop-up book provides a highly valid and practical instructional medium for elementary science learning, particularly in ecosystem topics. The high validity scores obtained from media experts (M = 4.63; Aiken's V = 0.89) and subject matter experts (M = 4.61; Aiken's V = 0.90) indicate that the developed media meets both pedagogical and technical standards required for instructional feasibility. In addition, the practicality score (M = 4.78; 95.67%) indicates that the media was positively accepted by students and considered easy to use in classroom learning activities. These findings indicate that the developed product has strong feasibility for classroom implementation, both from expert judgment and user response perspectives.

The results of the Define stage also provide important empirical support for the product development process. The needs analysis showed that 89% of students required visual learning media, 87% of learning activities still relied on textbooks, and 84% showed limited use of interactive media. These findings explain why the developed media received high validity and practicality scores, as the product was specifically designed to address the instructional gaps identified during the preliminary analysis. This demonstrates a strong alignment between user needs and product design.

These results are consistent with the growing body of literature emphasizing the role of augmented reality in supporting interactive learning experiences. Augmented Reality has been recognized as a technology capable of integrating real and virtual environments, thereby facilitating immersive and interactive learning processes [50]. The integration of augmented reality into instructional media allows abstract concepts to be visualized dynamically, which is particularly important in science learning where many phenomena are not directly observable [51]-[53]. In this study, this was reflected in the high media expert score for visual design (M = 4.70), indicating that the visualization component was one of the strongest aspects of the developed media.

The need for concrete and interactive learning media identified in the Define stage aligns with cognitive development theory proposed by Jean Piaget. According to Piaget, elementary school students are in the concrete operational stage, where they require tangible and visual representations to understand abstract concepts [54]. The developed augmented reality based pop-up book directly addresses this need by combining physical three-dimensional structures with digital augmentation, enabling students to interact with ecosystem components in a more concrete and contextual manner. This alignment may explain the high practicality score in ease of use (M = 4.85), as the media design was adapted to students' developmental characteristics.

Furthermore, the integration of pop-up book elements with AR features reflects the principles of multimedia learning theory proposed by Richard E. Mayer. Mayer emphasizes that learning is more effective when information is presented through both verbal and visual channels [55]. In this study, students interacted with textual explanations, physical pop-up visuals, and augmented reality based animations simultaneously, which supports multimodal learning experiences. This finding is consistent with previous studies highlighting the importance of multiple representations in supporting conceptual learning [56], [57].

The findings of this study are also consistent with previous research indicating that AR-based instructional media increase student motivation and engagement [58], [59]. However, unlike previous studies that often focused on fully digital AR applications, this study integrated augmented reality with physical pop-up books. This hybrid approach represents the main novelty of this research, as it combines tactile and digital interaction in one instructional medium. This hybrid model provides students with opportunities to interact physically with printed materials while simultaneously exploring digital ecosystem simulations.

Compared to previous studies that focused only on augmented reality applications or conventional pop-up books Casteleiro-Pitrez [60], this study provides a more integrated approach by combining physical and digital instructional environments. This integration responds to the limitations identified in previous studies, where digital-only media often lacked tactile interaction, while printed media lacked dynamic visualization.

The practicality results showed that 92% of student responses were positive (strongly agree and agree), indicating strong acceptance of the developed instructional media. Students reported that the media was easy to operate, visually attractive, and helpful for conceptual visualization. This finding is supported by previous studies indicating that augmented reality based learning environments significantly enhance student engagement [61], [62]. The high practicality score in learning benefits (97%) suggests that students perceived the media as useful in supporting their ecosystem learning experiences.

From a pedagogical perspective, the structured design of the media, including gradual content presentation and contextual examples, supports scaffolding in learning. This is in line with the social constructivist theory proposed by Lev Vygotsky, which emphasizes the importance of guided learning and interaction in knowledge construction [63]. The augmented reality features provide immediate visual feedback and contextual information, enabling students to explore ecosystem relationships through guided interaction[64].

The practical implication of this study is that teachers can use augmented reality based pop-up books as alternative instructional media to support science learning, particularly for abstract topics requiring visualization. The developed media can also reduce dependence on conventional textbook-based instruction and increase classroom interaction through active student engagement.

Moreover, the findings reinforce the importance of systematic instructional media design. The high validity scores indicate that the media successfully integrates content accuracy, visual design, and technological functionality. This supports the argument that well-designed instructional media can improve instructional quality and user experience [65], [66]. In addition, the use of systematic development models, such as the 4D model [67], ensures that the media is developed through iterative and evidence-based processes.

Despite the positive findings, it is important to acknowledge certain limitations. The augmented reality features in the initial product were limited in terms of interactive animations, and further development could enhance user interaction [68], [69]. Additionally, this study focused primarily on validity and practicality, without measuring experimental effectiveness or long-term learning outcomes. Therefore, the findings of this study should be interpreted within the scope of product feasibility rather than instructional effectiveness. Future research could explore the effectiveness of augmented reality based pop-up books in improving students' academic achievement, critical thinking, and scientific literacy. Further studies may also compare augmented reality based pop-up books with other digital instructional media to examine their relative effectiveness in elementary science learning contexts.

In conclusion, this study provides empirical evidence that the integration of augmented reality with pop-up book media is a feasible and practical approach to addressing challenges in elementary science learning. By combining theoretical foundations from cognitive development, multimedia learning, and constructivist perspectives, the developed media offers an innovative instructional alternative for supporting conceptual visualization and student engagement. The findings indicate that the developed media successfully integrates physical learning interaction with digital visualization, enabling students to explore ecosystem concepts through more concrete, contextual, and interactive learning experiences. The hybrid integration between pop-up structures and augmented realityvisualization also strengthens tactile engagement, which is highly relevant to the cognitive characteristics of elementary school students.

From a technological perspective, the developed augmented reality system demonstrated stable computational and interaction performance, achieving marker detection accuracy of 96.4%, average response time of 428 ms, stable rendering performance of 29–32 fps, and a System Usability Scale (SUS) score of 87.2, indicating excellent usability. Compared with augmented reality nly instructional systems, the developed hybrid AR-print interaction model provided more effective physical–digital integration while maintaining stable visualization performance on low- and mid-specification Android devices. The marker-based ecosystem visualization system was also optimized for low-resource classroom environments, making it more applicable for elementary schools with limited technological infrastructure. Therefore, the main contribution of this study lies not only in instructional media feasibility but also in the development of a technically reliable hybrid media technology system integrating marker-based augmented reality visualization, physical interaction, and computational optimization for elementary science learning.

4. CONCLUSION

This study successfully developed an augmented reality based ecosystem pop-up book as an innovative and interactive instructional medium for elementary science learning. The developed system integrates physical pop-up book structures with marker-based augmented reality visualization to support hybrid interactive learning experiences. The research objective, namely to develop instructional media that are valid and practical for supporting ecosystem learning in elementary education, has been achieved based on the results of product validation and practicality testing. The validation results showed that the developed media achieved a very valid category, with an average score of 92.6% from media experts and 92.2% from subject matter experts. These findings indicate that the instructional media meet feasibility standards in terms of visual design, content accuracy, curriculum relevance, and technological integration. In addition, the practicality test involving 139 elementary school students resulted in a score of 95.67%, indicating that the media are highly practical and well accepted by students in classroom learning activities. From a technological perspective, the augmented reality system also demonstrated stable computational performance, achieving marker detection accuracy of 96.4%, tracking stability of 93.8%, average response time of 428 ms, stable rendering performance of 29–32 fps, and a System Usability Scale (SUS) score of 87.2. The main contribution of this study lies in the integration of physical pop-up book structures with Augmented Reality technology, creating a hybrid instructional medium that combines tactile and digital learning experiences. This study also contributes to the development of a hybrid augmented reality -print interaction model and a marker-based ecosystem visualization system optimized for low-resource classroom environments and Android-based mobile devices. This integration provides an alternative approach for supporting the visualization of abstract ecosystem concepts in elementary science learning. Future studies are recommended to examine the effectiveness of the developed media on students' academic achievement, conceptual understanding, and critical thinking skills, as well as to explore more advanced augmented reality interaction features, adaptive visualization systems, and broader implementation across different educational contexts and science topics.

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AUTHOR CONTRIBUTIONS
Conceptualization was carried out by M.B.I.S. and S.E.P.; methodology by M.B.I.S.; software development by M.B.I.S.; validation by M.B.I.S., S.E.P., F., and B.S.; formal analysis by M.B.I.S.; investigation by M.B.I.S.; data curation by M.B.I.S.; writing—original draft preparation by M.B.I.S.; writing—review and editing by S.E.P., F., and B.S.; visualization by M.B.I.S.; supervision by S.E.P., F., and B.S. All authors have read and approved the final manuscript.

INFORMED CONSENT STATEMENT
Informed consent was obtained from all participants involved in this study. Since the participants were elementary school students, permission was obtained from their parents or legal guardians prior to participation. Approval was also obtained from the participating schools and teachers before the implementation of the study. Participants and their guardians were informed about the objectives and procedures of the research, and participation was entirely voluntary. All collected data were treated confidentially, anonymized during analysis, and used solely for research purposes.

CONFLICTS OF INTEREST
The authors declare that this research was conducted in the absence of any personal, professional, or financial relationships that could be perceived as a potential conflict of interest. No external interests influenced the research process, data analysis, interpretation of results, or manuscript preparation and publication.

USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY
The authors declare that during the preparation of this work, AI-assisted tools including ChatGPT, QuillBot, and Grammarly were used to support language refinement, paraphrasing, and improvement of clarity and readability. After using these tools, the authors carefully reviewed and edited the content as needed and take full responsibility for the content of this publication.

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