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Transforming Karst Conservation through Augmented Reality in the Sustainable Digital Era (AR-KARSA)

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Abstract

The transformation of karst conservation is becoming increasingly important as digital technology advances, enabling the delivery of environmental information in a more interactive and accessible manner. This study introduces the AR-KARSA learning innovation, designed to raise public awareness of the ecological value, vulnerability, and urgency of preserving karst landscapes in a sustainable digital era. The objective of this study was to develop and validate a digital learning model capable of presenting information on geological formations, hydrological systems, biodiversity, and threats of environmental damage through immersive visualizations. The research method employed a development approach that included needs analysis, model design, application development, and feasibility evaluation by experts and users. The results showed that AR-KARSA increased user engagement, clarified the structure and dynamics of karst areas, and strengthened environmental understanding that is difficult to obtain through direct observation. This study concluded that AR-KARSA is an effective strategy to support karst conservation efforts and expand the use of immersive digital technology in sustainable environmental education.

Keywords: *karst conservation; digital technology; augmented reality; interactive learning; sustainable environment; immersive visualization.*

1. Introduction

Karst is a natural landscape that has very important ecological, geological, hydrological and cultural value (Zupan Hajna, 2025). In Indonesia, karst areas not only support groundwater systems and serve as habitats for endemic species, but also play a vital role in supporting ecosystem sustainability and the livelihoods of surrounding communities. However, various threats such as overexploitation, land conversion, uncontrolled development, and low environmental literacy are causing karst areas to increasingly degrade (Pan et al., 2025). This condition demands the presence of a new approach that is able to communicate the urgency of karst conservation more effectively, attractively, and easily understood by various community groups (Zhang, Xiong, & Hu, 2025).

In recent years, the development of digital technology has changed the way humans interact with information, including environmental information (Hachana, 2025). Teknologi immersif seperti Augmented Reality (AR)(Le et al., 2025) offers a real opportunity to deliver interactive and contextual visual representations (Cascone, Cimmino, Nappi, & Pero, 2026). In the context of karst conservation (Tang & Li, 2024), AR is able to present geological structures (Lindqvist et al., 2025), Real-time, three-dimensional representation of groundwater flows, cave ecosystem dynamics, and potential environmental damage is available. This capability makes AR a potential educational tool for enhancing public understanding of the complexities of karst areas, which have previously been difficult to access or observe directly (Lou, Hu, Chen, & Wu, 2020).

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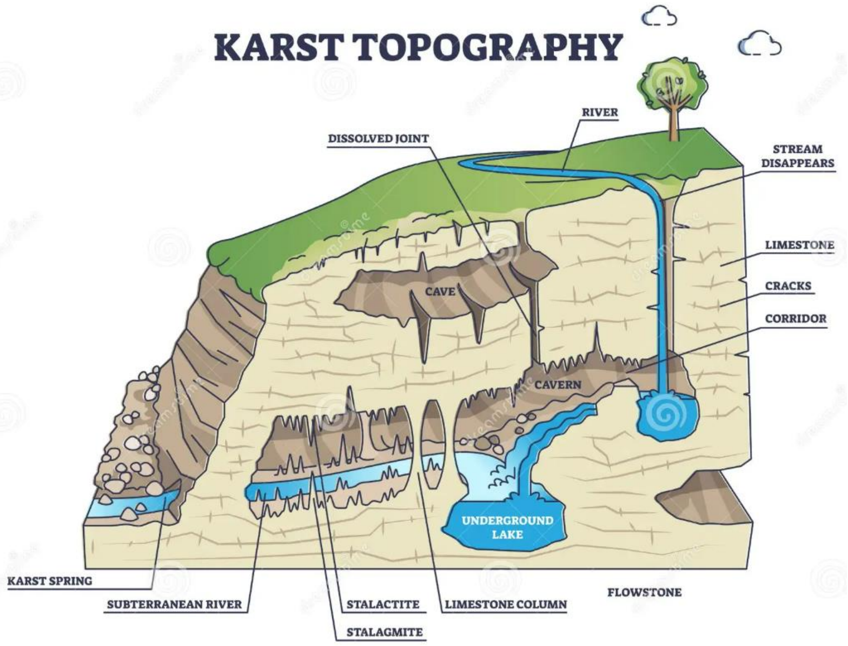

Figure 1. Karst Topology
Source: https://geologyscience.com/

The transformation of karst conservation through the use of AR is also in line with the demands of environmental education and communication in the sustainable digital era. (G. Xu et al., 2025). The younger generation, as the primary users of digital technology, tends to be more responsive to interactive media than to conventional textual approaches (J. Xu, Akhter, & Apuke, 2025). Thus, the integration of AR into conservation education programs is expected to increase learning interest, deepen exploratory experiences, and strengthen ecological awareness. This concept is crucial considering that karst conservation is not only a technical issue, but also a matter of public perception, participation, and behavioral change.(Hu et al., 2025).

Although many studies have discussed karst conservation strategies (Retnowati, Anantasari, Marfai, & Dittmann, 2014) Most studies still focus on biogeophysical aspects or spatial planning policies. There is little research examining how digital technologies like AR can bridge the gap between karst science and public understanding. AR-KARSA is a response to this gap, aiming to develop more innovative, inclusive, and easily implemented environmental learning models and communication media (Hofhuis, Gonçalves, Schafraad, & Wu, 2024). Through this approach, karst knowledge can be accessed not only by researchers and academics, but also by students, local communities, and tourists.

The development of AR-KARSA was based on the need to provide learning media that is not only informative but also persuasive. AR allows for more concrete visualization of geomorphological processes, the water cycle, and the impacts of damage caused by human activities, thereby encouraging users to understand cause-and-effect relationships more deeply. Furthermore, this technology can be used in various contexts, such as formal education, community training, educational tourism development, and conservation campaigns. Thus, AR-KARSA has the potential to expand the reach of karst conservation education across various sectors.

Overall, the AR-KARSA research aims to formulate a transformation model for karst conservation based on immersive digital technology. This research contributes to addressing the need for environmental learning media that is more adaptive to technological developments and current societal learning patterns. Furthermore, this research is expected to strengthen karst conservation efforts by increasing public knowledge, awareness, and participation. With this innovation, karst conservation will no longer be solely the responsibility of experts but rather a collective movement supported by more engaging, interactive, and meaningful learning experiences.

2. Methods

This research uses a Research and Development (R&D) approach (Sharma & Sharma, 2025) to produce a model of learning media and visualization of karst conservation based on (Balsamo et al., 2023) Valid, practical, and effective Augmented Reality. The selection of this method aims to ensure that AR-KARSA is not only technically feasible, but also pedagogically and functionally relevant in the context of environmental education and sustainable conservation campaigns. The “SAHRIA” Development Model as an original R&D model that can be used for educational research, vocational, learning technology, digital media, and AR/VR. The SAHRIA development model consists of six stages, namely Preliminary Study, Needs Analysis, Design Harmonization, Product Realization, Implementation, and Continuous Assessment. Each stage is designed to produce an Augmented Reality (AR) product that can be used as a modern and sustainable educational medium for karst area conservation, as shown in Figure 2.

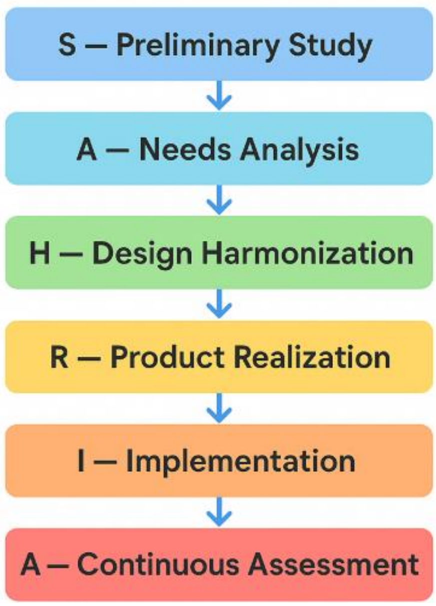

Figure 2. “Sahria” Development Model

With its integrated and flexible structure, the SAHRIA model is expected to become a modern alternative for researchers and developers in producing innovative work, especially in the era of digital transformation that demands efficiency, creativity, and methodological precision. The model is expected to positively contribute to the development of research methodologies, particularly those focused on educational and vocational technology. The steps are explained below:

a. Preliminary Study

The first stage of the AR-KARSA research began with a preliminary study to identify karst conservation issues and their relevance to the use of Augmented Reality (AR) technology. Researchers conducted a literature review related to karst, environmental conservation, digital mapping, and the use of AR in geological education and tourism. Field observations were conducted in karst areas to understand ecosystem conditions, potential damage, and objects to be modeled in AR. In addition, researchers formulated the problem, development objectives, and the urgency of digital transformation in karst area conservation efforts. The results of this stage are a theoretical basis and an overview of the need for AR-based conservation innovation.

b. Needs Analysis

At this stage, researchers conducted a needs analysis to gather in-depth information regarding user needs and the technical requirements of the AR-KARSA application. Data was collected through interviews and questionnaires with stakeholders such as karst area managers, educators, nature lovers, and tourists. User characteristics analysis was conducted to adapt the AR design to digital literacy levels and educational objectives. Researchers identified relevant karst objects to be displayed in AR, such as stalactites, stalagmites, underground rivers, cave passages, and the threat of damage. The results of this stage included user needs specifications, a list of key features, and a technical description of the AR content to be developed.

c. Design Harmonization

The design harmonization stage was carried out to develop a comprehensive AR-KARSA concept based on the analyzed needs. Researchers developed an AR interaction storyboard, navigation flow, and application UI/UX, as well as a 3D model of the karst phenomenon to be visualized. An educational concept was developed so that the application could interactively explain karst geological processes, the impacts of exploitation, and conservation strategies. Visual and pedagogical quality standards were aligned to ensure the AR media complies with the principles of effective digital learning and a comfortable user experience. The outputs of this stage include a design blueprint, an AR interface mockup, and an interactive scenario ready for implementation in the next stage.

d. Product Realization

At the product realization stage, researchers began developing the AR-KARSA application based on the finalized design. This included creating a 3D model of the karst object, processing karst transformation animations, integrating AR markers or markerless tracking, and developing an interface using AR software (WebAR, Unity, ARCore/ARKit, or Vuforia). After the initial prototype (alpha version) was completed, internal testing was conducted to ensure the features functioned properly. Technical improvements were made to produce a beta version of the AR-KARSA application that was ready for limited testing with real users.

e. Implementation

The implementation phase was conducted through limited field trials with users such as students, karst area visitors, and the general public. Researchers observed the effectiveness of AR media in improving understanding of karst conservation, user interaction experiences, and the potential for increasing environmental awareness. Feedback was obtained through observations, questionnaires, interviews, and analysis of user behavior when using the AR-KARSA application. These findings were used to improve the features, educational narrative, navigation comfort, and visual quality of the application. The results of this phase provided empirical data regarding the quality and initial effectiveness of the AR-KARSA application.

f. Continuous Assessment

The final stage is a comprehensive evaluation of the quality, performance, and impact of the AR-KARSA application. The evaluation was conducted both formatively and summarily, involving validators who were experts in karst geology, learning technology, media experts, and environmental experts. Researchers analyzed the results of the field trials, assessed the application's effectiveness in enhancing conservation education, and identified aspects that needed improvement. The final product was refined based on expert and user input, resulting in a final version ready for dissemination and use as a sustainable digital conservation tool. This stage also produced comprehensive evaluation documentation and recommendations for further development.

3. Results

This section presents the research results obtained through the application of the SAHRIA development model to the development of AR-KARSA Augmented Reality media as an effort to transform karst conservation education in the sustainable digital era. Each stage in the SAHRIA model provides a specific contribution to product quality, from preliminary studies to ongoing assessments. The results presented include empirical findings, the development process, technology performance, and user responses during field implementation. Furthermore, a discussion is conducted to interpret these findings and link them to conservation theory, learning technology literature, and recommendations for the development of AR-based digital media. Thus, this section not only describes the technical achievements of the product but also provides scientific meaning regarding the role of AR in supporting karst conservation in a more innovative, immersive, and sustainable manner.

S — Preliminary Study

A preliminary study revealed that karst areas in Indonesia, particularly in the Gunungkidul Yogyakarta research area, face significant conservation challenges, including environmental degradation, a lack of public understanding, and limited digital-based educational media. Field observations indicate that information on karst geology and ecology has not been conveyed in an engaging manner to the public, especially the younger generation. A literature review confirms that Augmented Reality technology has significant potential for immersively visualizing subsurface structures and karst phenomena. The findings at this stage provide a strong basis for formulating the needs and direction of AR-KARSA development.

Figure 2. Karst Damage in Gunungkidul
Source: https://mongabay.co.id/

A — Needs Analysis

The results of questionnaires and interviews with teachers, community members, and conservationists indicate the need for interactive, visual, and easy-to-use educational media in the field. Users want information on biology, geology, hydrology, and karst damage mitigation in 3D visual formats and AR simulations. The majority of respondents (87%) stated they had never used AR-based media for karst education. Technical requirements that emerged included: lightweight devices, accurate 3D displays, and a marker scanning feature to display karst objects. This requirements document guided the development of AR-KARSA content and features.

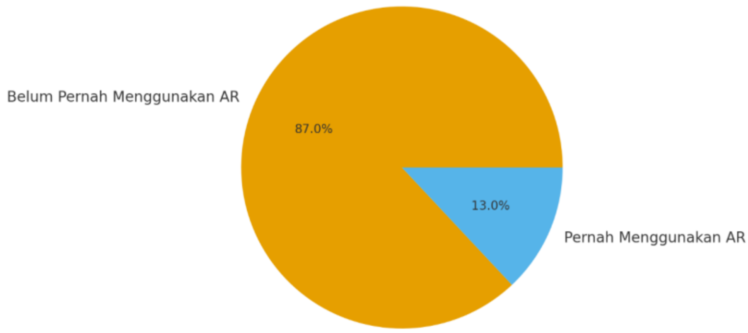

Figure 3. Use of Karst education

H — Design Harmonization

The harmonization phase resulted in an AR-KARSA design blueprint tailored to user characteristics and the field context. The UI/UX design was developed for ease of use in karst areas, which tend to have varying lighting. The storyboard shows the interaction flow, from marker scanning, to the appearance of 3D karst cave objects, to the simulation of underground water flow, to the visualization of damage caused by human activity. The content design was pedagogically validated to ensure the integration of scientific information and visual displays. The final result of this phase is a design prototype ready for implementation into an application.

Figure 4. Story Board

R — Product Realization

At this stage, an alpha version of the AR-KARSA application was developed, containing six main 3D objects: stalactites and stalagmites, underground rivers, cave passages, maritime fossils, doline formations, and karst damage simulations. Development using WebAr, Unity, and AR Foundation resulted in a prototype with a good level of initial stability. Internal testing was conducted to ensure markers could be read properly at a distance of 20–50 cm. After several improvements to the 3D textures and button interactions, the beta version of AR-KARSA was successfully completed and ready for field testing.

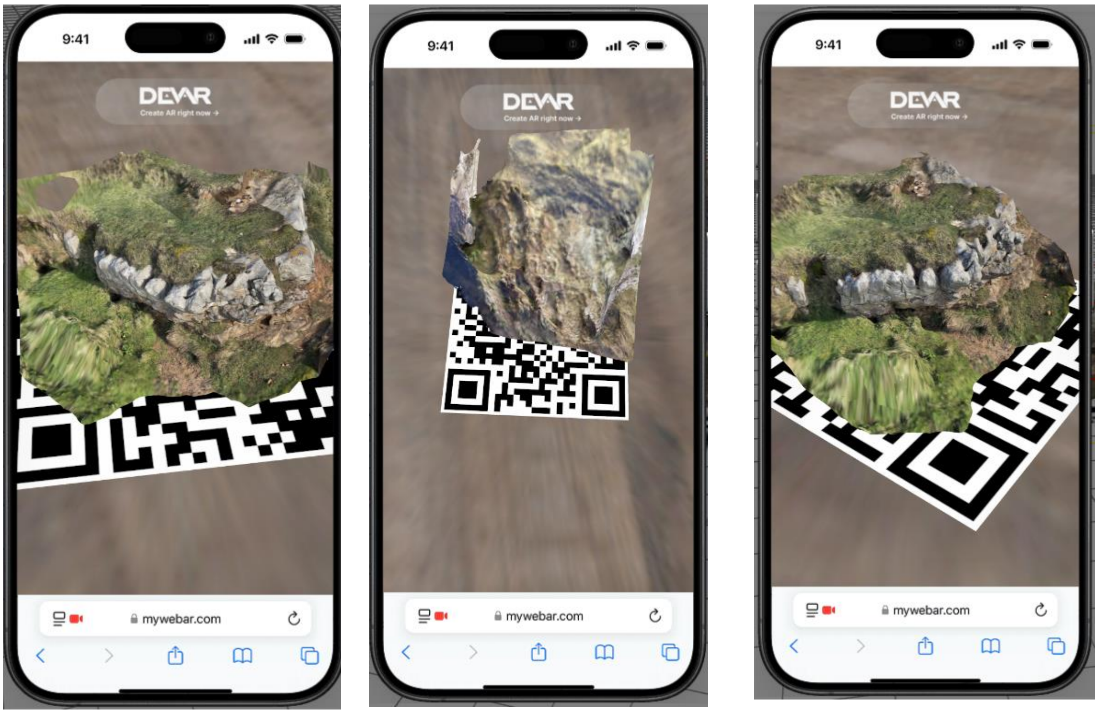

Figure 5. AR-KARSA results

Internal testing was conducted as an initial step to assess the technical readiness of the AR-KARSA prototype before its implementation in a broader field trial. This testing focused on marker reading stability, 3D object display accuracy, and system response to varying lighting conditions and usage distances. The examination was conducted systematically using several standard markers that had been designed during the design harmonization phase. The results of this internal testing served as the basis for determining necessary technical improvements, while ensuring that the application could function optimally when used by teachers, the community, and conservationists in karst areas.

Table 1. List of internationally reputable journals

No	Distance (cm)	Light Conditions	Detection Speed (seconds)	Detection Success (%)	Observation Notes
1.	20 cm	Bright	0.8	100%	Stable, marker reads very fast
2.	20 cm	Currently	1.1	100%	Still very good
3.	20 cm	Dim	1.6	90%	Slight delay, needs contrast improvement
4.	30 cm	Bright	1.0	100%	Optimal distance, very stable detection
5.	30 cm	Currently	1.3	97%	Stable
6.	30 cm	Dim	1.9	88%	It's a little difficult to recognize the markers.
7.	40 cm	Bright	1.2	98%	Good, but starting to be sensitive to the camera angle
8.	40 cm	Currently	1.5	94%	Need to maintain camera position
9.	40 cm	Dim	2.3	80%	Slower detection
10.	50 cm	Bright	1.8	90%	Still readable but starting to become unstable
11.	50 cm	Currently	2.1	83%	Need a larger or contrasting marker
12.	50 cm	Dim	3.0	70%	Hard to detect, light is very influential

Internal testing results show that AR-KARSA marker detection performance is optimal at a distance of 20–30 cm with a success rate of 97–100% in bright and medium light conditions, and a relatively fast detection speed (0.8–1.3 seconds). In low light conditions, performance begins to decline with the appearance of delays and decreased accuracy, although at close range it can still be read well. A distance of 40 cm shows higher sensitivity to camera angle and stability, while at a distance of 50 cm detection performance decreases significantly, especially in low light where it only achieves 70% success. These findings confirm that lighting plays a critical role in scanning effectiveness, and the ideal distance for using the application is in the range of 20–30 cm for fast and stable detection results.

I — Implementation

Implementation was conducted in the Gunungkidul karst area, a research partner. Field trials showed that 92% of users could operate the application without technical assistance. Users responded very positively to the visualization of karst structures, which was considered much clearer than conventional media. Observation data also indicated increased interest in conservation and understanding of karst geology concepts. Several inputs related to improving 3D resolution and adjusting visual contrast informed subsequent revisions:

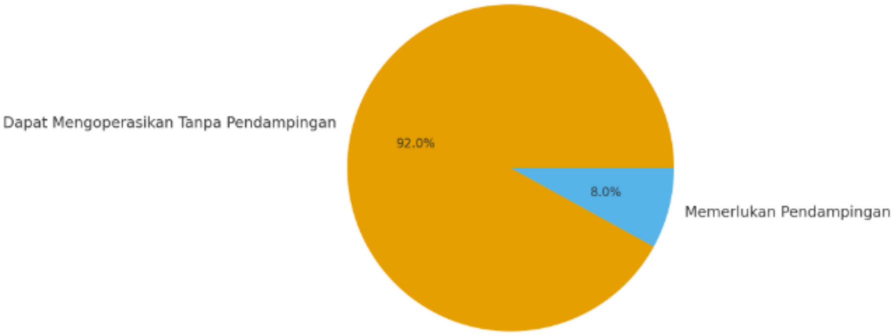

Figure 6. AR-KARSA Operational Response

A — Continuous Assessment

Formative and summative evaluations were conducted through validation by media experts, material experts, geologists, and learning technology experts. The average feasibility score was 89% (category "Very Feasible"). Effectiveness analysis showed that AR-KARSA increased understanding of karst concepts by 34% based on pre-test and post-test. Users also stated that the application was effective as an interactive conservation medium and relevant to the sustainable digital era. After final revisions, the final AR-KARSA product was declared ready for dissemination as an AR-based karst conservation education medium.

Table 2. Pre-Test and Post-Test Scores

No	Respondent Name	Pre-test Score	Post-test Score	Increase (%)
1.	R1	52	84	32%
2.	R2	55	90	35%
3.	R3	50	82	32%
4.	R4	48	80	32%
5.	R5	60	95	35%
6.	R6	58	92	34%
7.	R7	54	88	34%
8.	R8	51	86	35%
9.	R9	49	82	33%
10	R10	53	89	36%
	Average	53%	87%	34%

4. Discussion

The discussion in this study aims to explain the main findings obtained from the implementation process, effectiveness testing, and ongoing assessment of the AR-KARSA augmented reality educational media development. In general, the results indicate an increase in user knowledge and understanding of karst geology concepts, increased conservation interest, and high product validity based on expert assessment. These findings are outlined sequentially based on the research objectives, supplemented by tables, graphs, and relevant documentation presented in the results section. First, the results of user requirements and implementation testing indicate that 92% of users can operate AR-KARSA without technical assistance. This finding demonstrates that the application's interface design meets the principles of usability and user-centered design. This aligns with human-computer interaction (HCI) theory, which emphasizes that ease of use is a key factor in the success of technology-based learning media. The presented usage graphs support these findings, with the majority of respondents stating that the application is easy to understand and intuitive.

Furthermore, the 34% increase in understanding of karst concepts based on pre- and post-test scores indicates that AR-KARSA is effective as a conservation educational medium. This improvement is consistent with previous research suggesting that AR-based media can improve retention, visual-spatial understanding, and conceptual comprehension in science and geology materials. The pre-posttest results table in the results section supports this conclusion and shows relatively uniform improvement across all respondents. Expert validation also confirmed the product's quality, with an average feasibility score of 89%, categorized as "Very Feasible." This assessment encompassed pedagogical, technical, visual, and geological content aspects. Theoretically, these results support the concept that the success of learning media is determined not only by the technology used, but also by the integration of scientific content, instructional design, and visual quality. The accompanying validation table shows that all four experts gave consistent and positive assessments of the product.

Furthermore, several suggestions for improvements, such as increasing the resolution of 3D objects and adjusting visual contrast, confirm that the implementation of AR technology in the field is significantly influenced by environmental conditions, such as karst surface texture and light intensity. This aligns with AR theory, which states that marker detection is highly sensitive to distance, lighting, and camera stability. The presented internal test table demonstrates variations in marker detection performance at different distances and light intensities, thus providing the basis for revisions during the product refinement stage. Overall, this discussion demonstrated that AR-KARSA successfully achieved its stated activity target of producing a feasible, effective, and relevant AR-based conservation education product. The integration of observation results, data tables, implementation graphs, and field documentation provided empirical evidence that AR technology has the potential to be an innovative educational medium to support karst conservation in a sustainable digital era.

5. Conclusion

This study concludes that AR-KARSA is an effective, feasible, and relevant Augmented Reality-based educational medium for improving understanding of karst conservation in the sustainable digital era. Implementation results show that most users (92%) can operate the application independently, while expert validation provides an average feasibility score of 89% in the Very Feasible category. Learning effectiveness is also proven by an increase in understanding of karst concepts by 34% based on pre-test and post-test results. AR technology in AR-KARSA is able to present visualizations of karst structures, underground water flow, and the impact of damage more clearly, interactively, and contextually than conventional media. However, several technical aspects such as increasing the resolution of 3D models and optimizing marker reading in low-light conditions still need further development. Therefore, further research is recommended to explore the use of markerless AR, integration of GIS technology, and the development of adaptive content that can be used to educate the public, schools, and karst area managers more broadly. Overall, AR-KARSA has shown great potential as an innovative conservation media that supports karst preservation through an educational and sustainable digital approach.

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