



## Development of Immersive Augmented Reality Learning Media Integrated with Ethnoscience: A Design-Based Research Approach

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### ABSTRACT

**Purpose of the study:** This study aimed to develop, validate, and evaluate an Augmented Reality (AR)-based e-module integrated with Madurese bull-racing ethnoscience (SMART) to enhance junior high school students' numeracy skills and scientific literacy through contextualized and meaningful science learning experiences.

**Methodology:** This study employed a Design-Based Research (DBR) approach based on the Reeves model, combined with a quasi-experimental pretest–posttest control group design. The participants consisted of 64 eighth-grade students from junior high schools in East Java, Indonesia. Data were collected through expert validation sheets, Likert-scale questionnaires, classroom observations, and achievement tests. The data were analyzed using Aiken's  $V$ , normalized gain ( $N$ -gain), ANCOVA, and Cohen's  $d$  effect size analysis.

**Main Findings:** The SMART e-module demonstrated high validity (Aiken's  $V = 0.87$ ) and excellent practicality (88.6%). The experimental group showed greater improvements in numeracy and scientific literacy than the control group, with  $N$ -gain scores ranging from 0.65 to 0.72, indicating moderate-to-high learning gains. ANCOVA results revealed a significant effect of the intervention on students' learning outcomes ( $F(1,61) = 18.74, p < 0.001, \eta^2 = 0.23$ ). In addition, students exhibited consistently high levels of behavioral, emotional, and cognitive engagement throughout the learning process.

**Novelty/Originality of this study:** This study presents an innovative integration of Augmented Reality technology and Madurese ethnoscience within a Design-Based Research framework to support contextual science learning. The study contributes to the existing literature by demonstrating that culturally responsive AR-based learning materials can effectively foster conceptual understanding, scientific reasoning, numeracy proficiency, and higher-order thinking skills simultaneously.

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## 1. INTRODUCTION

In line with the global agenda of Education for Sustainable Development (ESD) and Indonesia's Golden Generation 2045 vision, education is expected to equip learners with essential competencies, including literacy, numeracy, scientific literacy, and global competence, to support sustainable development and achieve the Sustainable Development Goals (SDGs) [1]-[5]. These competencies require critical thinking, communication, and contextual information-processing skills, extending literacy beyond basic reading toward analytical and reflective engagement [6]-[9]. However, Indonesia continues to face significant challenges in developing these competencies. PISA results indicate a persistent decline in student achievement, particularly in numeracy, with scores decreasing from 386 in 2015 to 359 in 2022, while performance in reading, mathematics, and science remains substantially below OECD averages [10].

Similarly, INAP results revealed relatively low literacy achievement compared with mathematics and science [11]. These findings suggest that many Indonesian students still operate at lower-order thinking levels and have not yet achieved adequate literacy and numeracy competencies, indicating limited effectiveness of current educational practices in fostering higher-order thinking and deep conceptual understanding [12]-[14]. Despite ongoing educational reforms, evidence shows that students continue to demonstrate weak numeracy and scientific literacy skills, with approximately 82% performing below the minimum proficiency benchmark in PISA 2022 [15]-[17]. These findings highlight the urgency of developing innovative and contextualized learning approaches that can simultaneously strengthen students' numeracy and scientific literacy skills. Given that numeracy and scientific literacy are essential for problem-solving and informed decision-making in everyday life, strengthening these competencies remains a critical priority for improving educational quality and preparing students to address real-world challenges [12], [17].

In the context of science education, scientific literacy refers to the ability to understand scientific concepts, communicate scientific ideas, and apply scientific knowledge in problem-solving while demonstrating awareness of social and environmental issues [18]-[21]. The Indonesian Ministry of Education and Culture also emphasizes that scientific literacy enables individuals to participate responsibly in discussions on scientific issues, including health and environmental concerns [22]-[24]. Individuals with strong scientific literacy tend to be more open to diversity, respectful of different perspectives, and more likely to exhibit critical, creative, skeptical, optimistic, and future-oriented attitudes when addressing scientific issues [25]-[29]. Scientific literacy further involves the ability to comprehend concepts, draw evidence-based conclusions, investigate problems using acquired information, and explain natural phenomena scientifically. Therefore, students need to develop critical thinking, problem-solving, creativity, communication, and collaboration skills through science learning and experimentation activities [21], [30].

Complementing scientific literacy, numeracy literacy is an essential competency that enables individuals to apply mathematical concepts and quantitative reasoning to understand, analyze, and interpret scientific information [31]-[34]. Numeracy encompasses the ability to use numerical concepts and mathematical operations in everyday life, interpret quantitative information, analyze data, estimate outcomes, and solve numerical problems [12], [31], [35]. In science education, numeracy plays a crucial role in supporting the understanding of measurements, data analysis, graph interpretation, and other quantitative aspects of scientific phenomena, thereby enabling students to develop a more systematic and measurable understanding of science [13], [33], [36]. Numeracy literacy also involves the ability to use mathematical reasoning, interpret mathematical representations, and communicate quantitative findings effectively [31], [37], while extending beyond computational skills to include conceptual understanding of the use of numbers and data in diverse contexts [38]. As interrelated competencies, scientific literacy and numeracy serve as fundamental foundations for critical thinking and problem-solving in science learning [39]-[41]. Scientific literacy supports the understanding and application of scientific knowledge [42]-[44], whereas numeracy facilitates the interpretation of mathematical representations and scientific data [33], [45]. Despite their importance, the development of these competencies remains constrained by limited reading proficiency, insufficient contextualized learning experiences, and restricted access to appropriate learning resources. Therefore, strengthening scientific literacy and numeracy through effective science education is essential to prepare students to address increasingly complex global challenges [46], [47].

Natural Science is closely associated with the development of numeracy literacy because many scientific concepts require quantitative reasoning and conceptual understanding [48], [49]. In science education, conceptual understanding is essential since scientific concepts are interconnected, particularly fundamental concepts such as motion and force [50]-[52]. However, previous studies have reported that students' understanding of motion and force remains relatively low due to the abstract and complex nature of the material [53]-[55]. Integrating local wisdom into science learning has been recognized as an effective approach to strengthening students' numeracy literacy and conceptual understanding by providing meaningful and contextualized learning experiences [13], [56], [57]. Such integration enables students to recognize the relevance of scientific concepts in everyday life [11], [58], [59]. One example of local wisdom related to motion and force is buffalo racing, which provides an authentic context for illustrating concepts such as speed, distance-time relationships, and the influence of mass on motion [60]-[62].

Previous studies have demonstrated that local wisdom can serve as a valuable resource for science learning and a contextual foundation for science instruction [59], [63], [64]. Research has also highlighted the close relationship between numeracy literacy and science learning outcomes [13], [36], [65]. Nevertheless, studies integrating local wisdom into learning have generally focused on broad pedagogical approaches, including discussion, observation, literature review, storytelling, practicum activities, field visits, deductive–inductive reasoning, dramatization, and question-and-answer methods, which are intended to promote student engagement, critical thinking, communication, and conceptual understanding [66]–[68]. Despite these efforts, no previous study has specifically examined the use of the Madurese buffalo-racing tradition (*Karapan Sapi*) as a contextual learning environment for exploring the relationship between numeracy literacy and students' understanding of motion and force concepts, thereby highlighting an important research gap addressed in the present study.

Local wisdom-based learning approaches have been shown to support the development of literacy, numeracy, and conceptual understanding by connecting academic content with students' real-life experiences [69], [70]. Therefore, incorporating contextual local wisdom, such as the Madurese buffalo-racing tradition (*Karapan Sapi*), into science learning provides meaningful opportunities to enhance students' numeracy and scientific literacy. One effective strategy for achieving this is through the development of contextual instructional materials [12], [71]. Accordingly, this study proposes an AR-integrated SMART (Science and Mathematics) e-module that combines numeracy-oriented science content, local cultural contexts, and Augmented Reality (AR) technology to support interactive and meaningful learning experiences [[72]–[75].

Recent studies have consistently demonstrated the effectiveness of Augmented Reality (AR) in improving learning outcomes, motivation, engagement, conceptual understanding, and knowledge retention in STEM education [74]–[78]. Through immersive and multimodal learning experiences, AR enables learners to interact with virtual objects, receive real-time feedback, and actively construct scientific understanding within authentic learning contexts [79]–[83]. Furthermore, mobile-based AR offers flexible and accessible learning opportunities, particularly in resource-constrained environments [84]–[86]. Despite these advantages, existing AR research has predominantly emphasized visualization and short-term learning outcomes, with limited attention to interaction design, usability, user experience, and culturally contextualized learning environments. In particular, the integration of scientific literacy, numeracy literacy, and ethnoscience-based local wisdom remains underexplored, while challenges related to teacher readiness, instructional design, and curriculum integration continue to hinder effective implementation [61], [75], [87]. Therefore, although AR has been empirically demonstrated to be both effective and promising in enhancing educational quality, there remains a pressing need to develop systematic, contextualized, and needs-based instructional models to ensure its optimal and sustainable implementation.



Figure 1. Visualization of the AR Bibliographic Network

Based on the bibliometric analysis presented in Figure 1, limited attention has been given to the integration of ethnoscience, numeracy literacy, and scientific literacy within AR-based science learning environments [87]. To address this gap, the present study develops an AR-integrated SMART (Science and Mathematics) e-module grounded in the Madurese bull-racing tradition (*Karapan Sapi*), integrating ethnoscience, interactive AR visualization, and numeracy-oriented scientific activities within a Design-Based Research (DBR) framework. Unlike previous studies that primarily focused on AR visualization, local wisdom integration, or literacy development as separate approaches, this study integrates these elements into a single culturally responsive and technology-enhanced learning environment. The novelty of this study lies in the integration of *Karapan Sapi*-based ethnoscience, AR technology, scientific literacy, and numeracy literacy within a SMART e-module specifically designed to support learning of motion and force concepts. Therefore, this study aims to (1) develop an AR-integrated SMART e-module grounded in the cultural context of Madurese bull racing (*Karapan Sapi*), (2) evaluate its validity and practicality, and (3) examine its effectiveness in enhancing students' numeracy and scientific literacy skills.

## 2. RESEARCH METHOD

### 2.1. Research Design

This study employed a Design-Based Research (DBR) approach to develop and validate an AR-based SMART e-Module integrated with local wisdom through iterative cycles of design, implementation, evaluation, and revision (Figure 2). Guided by the frameworks of Reeves and Wang & Hannafin [82], [88], DBR was selected because it enables the integration of product development, empirical evaluation, and theoretical contribution while ensuring high contextual relevance and ecological validity [89]-[91]. This approach was particularly suitable for developing the culturally contextualized AR-based e-Module, whose complexity could not be adequately examined using conventional experimental methods alone [92].

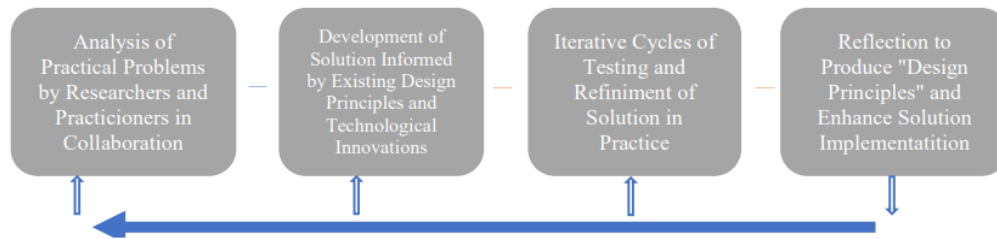


Figure 2. Reeves' (2006) Design-Based Research Framework

This study adopted Reeves' Design-Based Research (DBR) model, consisting of needs analysis, prototype development, and implementation. The needs analysis involved literature review, curriculum analysis, teacher interviews, and classroom observations to identify gaps in numeracy and scientific literacy. Subsequently, an AR-integrated SMART e-module based on the Madurese *Karapan Sapi* tradition was developed and validated by experts. The prototype was then implemented using a quasi-experimental pretest–posttest control group design to evaluate its effectiveness in improving students' numeracy and scientific literacy through pretest–posttest scores, classroom observations, and student response questionnaires.

Table 1. Research Design

Group	Pretest (O <sub>1</sub> )	Treatment	Posttest (O <sub>2</sub> )
Experimental Group	O <sub>1</sub>	EthnoScience-Based AR E-Module	O <sub>2</sub>
Control Group	O <sub>1</sub>	Conventional Instruction	O <sub>2</sub>

Note: O<sub>1</sub> = Pretest (baseline/initial ability); O<sub>2</sub> = Posttest (learning outcomes after the treatment)

This study employed a quasi-experimental pretest–posttest control group design. Students' initial numeracy and scientific literacy skills were assessed through a pretest, followed by six instructional sessions in which the experimental group learned using the AR-integrated SMART e-Module, while the control group received conventional instruction. Group assignment was conducted through cluster random sampling, and baseline equivalence was confirmed through homogeneity testing and pretest score matching. After the intervention, a posttest was administered to measure learning gains, while practicality and engagement data were collected using questionnaires and observation sheets. Quantitative data were analyzed using N-gain, independent-samples t-tests/ANCOVA, and effect size calculations, whereas qualitative data were examined through user response analysis. The findings were subsequently used to refine the product iteratively, ensuring its validity, practicality, and effectiveness.

### 2.2. Participants and Setting

The study involved 64 eighth-grade students (aged 13–14 years) from SMP Negeri 1 Pandeglang, a public junior secondary school in Pandeglang, Indonesia, who were assigned to an experimental group (n = 32) using the AR-based SMART e-Module and a control group (n = 32) receiving conventional instruction. Participants were selected through purposive sampling based on prior exposure to motion and force concepts, heterogeneous academic backgrounds, access to mobile devices, and full participation throughout the study. The intervention was conducted over five 90-minute sessions under equivalent classroom conditions, with both groups taught by the same teacher using identical learning materials and instructional duration to minimize bias. Baseline equivalence was established through pretest measures of numeracy and scientific literacy. A preliminary needs analysis indicated that more than 75% of students experienced difficulties in data interpretation, quantitative reasoning, and the application of motion and force concepts, highlighting the need for a contextualized AR-based learning intervention.

### 2.3. Product Development

The product developed in this study was the SMART e-module, a mobile-based augmented reality (AR)-integrated learning module designed to enhance students' scientific and numeracy literacy through the integration of AR technology and local cultural contexts. The e-module comprised four instructional units on motion and force, including fundamental concepts of motion, Newton's laws, force and acceleration, and real-life applications. These units were systematically organized through several learning stages: a contextual introduction based on the Madurese *Karapan Sapi* tradition, concept exploration using AR visualizations, data-driven numeracy activities, science literacy exercises modeled after AKM-type assessments, and reflective evaluation activities. The system also incorporated interactive manipulation mechanisms such as object rotation, zooming, and parameter manipulation to support students' conceptual understanding. The *Karapan Sapi* cultural context was utilized as an authentic learning scenario to connect physics concepts with real-world phenomena, including speed analysis, the effects of mass, and race-data interpretation. This integration was intended to create a more contextualized, meaningful, and relevant learning experience for students (see Figure 3).

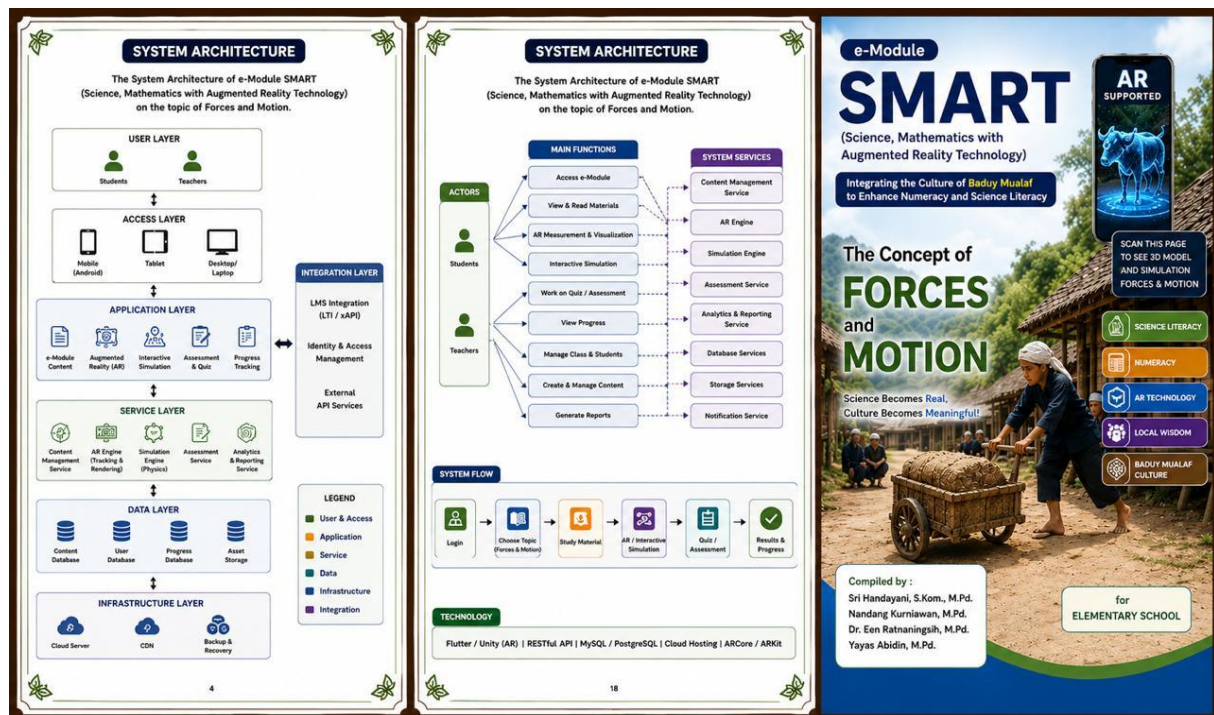


Figure 3. System Architecture

#### 2.3.1 System Architecture

The AR system architecture of the SMART e-Module employed a marker-based augmented reality approach developed using Unity 3D integrated with the Vuforia SDK. The overall architecture consisted of four interconnected layers: (1) the user interface layer, responsible for navigation and user interaction; (2) the marker detection and tracking layer, which utilized the Vuforia Engine to recognize predefined image targets and perform real-time spatial tracking; (3) the AR rendering engine layer, where Unity 3D processed and rendered interactive three-dimensional scientific visualizations; and (4) the instructional content layer, which delivered contextualized ethnoscience-based learning activities and numeracy tasks. The AR workflow began when the smartphone camera captured predefined image markers embedded within the learning module. These markers were subsequently processed through the Vuforia image target database, enabling feature-point recognition, marker identification, and real-time pose estimation. Once the marker was successfully detected, Unity 3D dynamically rendered anchored three-dimensional objects, animations, motion graphs, and scientific simulations onto the mobile display in real time. The rendering process enabled stable overlay synchronization between virtual objects and the physical environment, thereby supporting immersive and interactive learning experiences. The interactive AR environment allowed students to manipulate virtual objects through rotation, zooming, and parameter adjustment mechanisms to explore scientific relationships involving motion, force, acceleration, and mass within the contextual setting of the Madurese *karapan sapi* tradition. To improve tracking stability and rendering performance, high-contrast markers and optimized 3D assets were employed to ensure responsive visualization across various Android mobile devices and classroom lighting conditions.

### 2.3.2 Media Development Framework

The SMART e-Module was developed using a learner-centered media development framework that integrated UI/UX design principles, immersive interaction design, and multimedia learning strategies to support contextual science learning. The interface architecture emphasized usability, cognitive simplicity, visual consistency, accessibility, and interactive responsiveness to ensure efficient user interaction during AR-based learning activities. The interface design adopted a hierarchical navigation structure consisting of five primary components: (1) home interface, (2) topic selection menu, (3) AR scanning interface, (4) interactive learning activity page, and (5) reflective evaluation section. This navigation structure was intentionally designed to provide sequential learning guidance and minimize user disorientation during immersive exploration processes. The interaction flow was systematically organized to support active learning engagement. Students initially accessed conceptual materials through contextual ethnoscience-based introductions, followed by marker-scanning activities that activated AR visualization features. Subsequently, learners interacted with three-dimensional scientific simulations through object manipulation mechanisms, including rotation, zooming, and parameter adjustment, before completing numeracy and scientific reasoning tasks integrated within the learning environment. The interaction process concluded with reflective evaluation activities designed to reinforce conceptual understanding and scientific inference. Furthermore, the media design incorporated principles derived from the Cognitive Theory of Multimedia Learning and Cognitive Load Theory, including spatial contiguity, signaling, coherence, modality, and redundancy reduction principles. These principles were implemented to optimize dual-channel cognitive processing, reduce extraneous cognitive load, and strengthen students' visual-spatial representation and conceptual comprehension during immersive AR interaction. In addition, the interface responsiveness was optimized to maintain interaction stability and consistent visualization performance across different Android mobile devices and screen resolutions (see Figure 4).

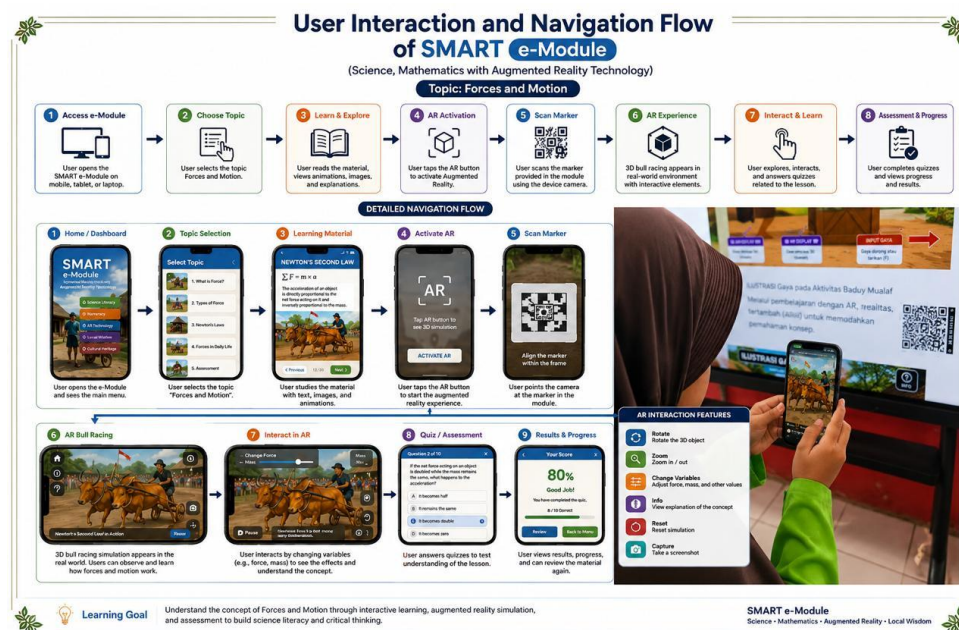


Figure 4. User Interaction and Navigation Flow of the SMART e-Module

### 2.3.3 Technical Media Components

The SMART e-Module employed a marker-based Augmented Reality (AR) system developed using Unity 3D integrated with the Vuforia SDK to support real-time interactive scientific visualization on Android mobile devices. The AR tracking mechanism operated through image-target recognition and pose estimation processes, in which the mobile camera detected predefined high-contrast markers containing sufficient feature points to ensure stable object recognition and spatial tracking under varying lighting conditions. Following marker detection, the rendering engine dynamically projected three-dimensional virtual objects, motion simulations, and graphical representations onto the physical environment in real time. To maintain rendering stability and interaction smoothness, the system implemented adaptive object scaling, lightweight texture compression, and frame-rate optimization techniques to reduce computational load and minimize latency across mid-range smartphone specifications. Rendering synchronization and asset optimization were also applied to preserve visualization consistency during user interaction, including object rotation, zooming, and parameter manipulation. In terms of mobile optimization and interface responsiveness, the SMART e-Module adopted a responsive user interface (UI) architecture capable of adapting to multiple Android screen resolutions and device dimensions while

maintaining interaction accuracy and visual coherence. The interface navigation was designed using touch-responsive layouts and simplified interaction flows to improve usability and reduce extraneous cognitive load during immersive learning activities. These technical optimizations ensured stable AR performance, efficient rendering processes, and consistent user experiences during classroom implementation (see Figure 5).

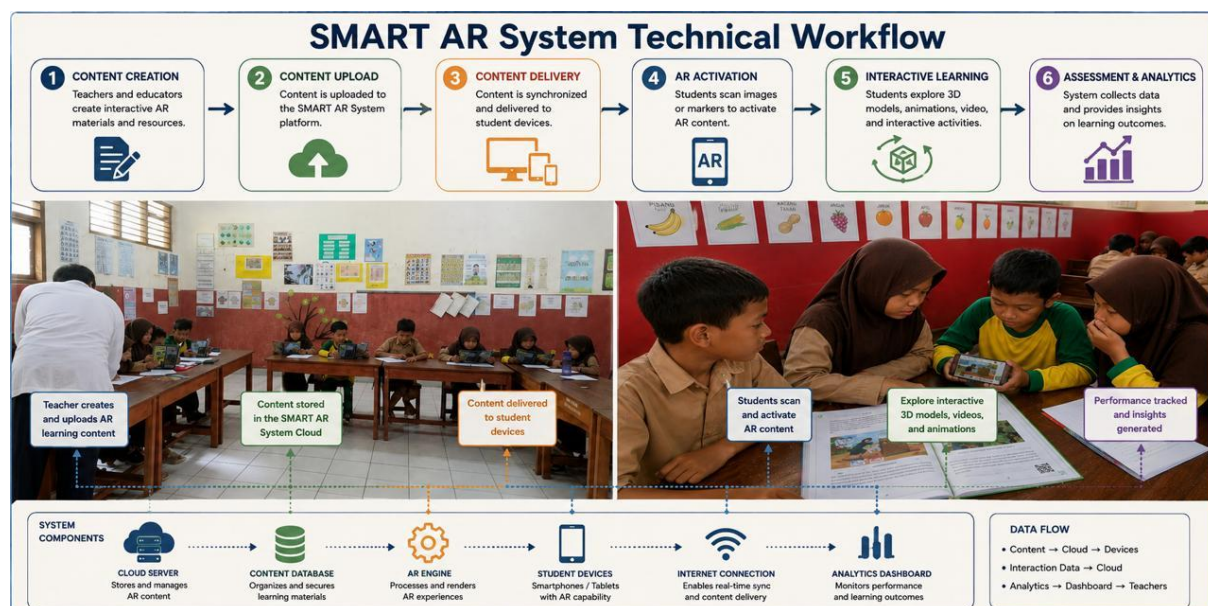


Figure 5. Technical Workflow of the SMART AR System

### 2.4 Instruments Test

The study employed several instruments to evaluate the validity, practicality, usability, and effectiveness of the AR-based SMART e-Module. All instruments underwent expert validation and reliability testing prior to implementation. Table 2 summarizes the instruments, indicators, validation procedures, reliability criteria, and analysis techniques used in this study.

Table 2. Research instruments and analysis criteria

Instrument	Purpose	Indicators/Components	Validity & Reliability Criteria	Analysis Technique
Expert Validation Sheet (25 items)	Evaluate content and design validity of the e-module	Curriculum alignment, conceptual accuracy, cultural integration, AR visualization, instructional design	Aiken's $V \geq 0.80$ ; $\alpha \geq 0.70$ ; CR $\geq 0.70$ ; AVE $\geq 0.50$	Content validity and reliability analysis
Practicality Questionnaire (20 items)	Assess practicality of the e-module	Ease of use, usefulness, implementation feasibility	$\alpha \geq 0.70$ ; Practicality $\geq 85\%$ = highly practical	Descriptive percentage analysis
AR Usability Instrument	Evaluate AR learning environment	Usability, user experience, system performance	Factor loading $> 0.50$ ; $\alpha = 0.91$ ; CR $\geq 0.70$ ; AVE $\geq 0.50$	EFA and CFA
Numeracy & Scientific Literacy Test (15 items)	Measure learning outcomes	Data interpretation (4), quantitative reasoning (4), phenomenon analysis (4), inference (3)	$r \geq 0.30$ ; $\alpha$ /KR-20 $\geq 0.70$	Item analysis, N-gain, ANCOVA
Essay Scoring Rubric	Assess higher-order responses	Conceptual understanding and reasoning	Cohen's Kappa $\geq 0.75$	Inter-rater reliability
Student Engagement Observation Sheet (12 indicators)	Measure learning engagement	Behavioral, emotional, cognitive engagement	$\alpha \geq 0.70$ ; Kappa $\geq 0.75$	

The instrument validation results indicated that all research instruments met the established validity and reliability criteria. The expert validation sheet achieved a high content validity coefficient (Aiken's  $V = 0.87$ ) and excellent internal consistency ( $\alpha = 0.91$ , CR = 0.93, AVE = 0.68). The practicality questionnaire also demonstrated

strong reliability across all constructs ( $\alpha = 0.89-0.92$ ), confirming its suitability for assessing users' perceptions of the AR-based SMART e-Module. Similarly, the numeracy and scientific literacy test showed good reliability ( $\alpha = 0.88$ ), with all items satisfying the validity requirements ( $r = 0.31-0.78$ ), moderate difficulty levels ( $p = 0.32-0.71$ ), and acceptable discrimination indices ( $D = 0.35-0.72$ ). Furthermore, strong agreement was observed between essay raters ( $\kappa = 0.81$ ), while the student engagement observation sheet demonstrated satisfactory reliability ( $\alpha = 0.87$ ) and inter-observer consistency ( $\kappa = 0.79$ ). Overall, these findings confirm that all instruments were valid, reliable, and appropriate for data collection.

**2.5 Data Analysis**

Data were analyzed using SPSS and AMOS at a significance level of  $\alpha = 0.05$ . Quantitative analysis included Shapiro–Wilk and Levene’s tests to assess normality and homogeneity assumptions, followed by N-gain analysis to measure improvements in numeracy and scientific literacy. ANCOVA was employed to examine post-test differences while controlling for pre-test scores, whereas independent-samples t-tests were conducted when appropriate [68], [93]. The magnitude of the intervention effect was determined using Cohen’s d effect size. Practicality and student engagement data were analyzed descriptively using mean scores and percentages. Qualitative data were analyzed through thematic analysis involving coding, categorization, and triangulation to enhance credibility. Finally, quantitative and qualitative findings were integrated through methodological triangulation to provide a comprehensive evaluation of the effectiveness, practicality, and implementation of the AR-based SMART e-Module.

**3. RESULTS AND DISCUSSION**

**3.1. Development Process**

The results of the DBR (Development Process) stage demonstrated that the AR-based SMART e-Module, developed through two iterative cycles of Design-Based Research (DBR), exhibited a consistent improvement in quality grounded in empirical evidence. A needs analysis involving 72 students revealed substantial difficulties in data interpretation (78.4%), quantitative reasoning (74.1%), and concepts related to motion and force (76.3%). These findings served as the foundation for strengthening the AR-oriented design and integrating the ethnoscientific context of Madurese *karapan sapi* culture. During Cycle I, the product achieved an Aiken’s V coefficient of 0.79, indicating several limitations in navigation (3.1/5), instructional clarity (3.2/5), and numeracy integration (3.0/5). Consequently, a series of revisions were implemented, including user interface simplification, enhanced AR interactivity, and stronger incorporation of numerical contexts. The results of Cycle II demonstrated a notable improvement, with Aiken’s V increasing to 0.87 and practicality scores rising from 76.5% to 88.6%. These findings confirm that systematic revisions informed by expert and user feedback were effective in producing a more valid, practical, and pedagogically feasible learning product for classroom implementation (see Table 3).

Table 3. DBR-Based Product Revisions

Aspect	Measurement	Cycle I (Mean ± SD)	Data-Driven Revision Actions	Cycle II (Mean ± SD)
Navigation	Ease of menu access and workflow clarity	3.12 ± 0.54 (Fair)	UI redesign, menu categorization, visual icons	4.32 ± 0.48 (Good)
Instructions	Clarity of language and task comprehensibility	3.18 ± 0.49 (Fair)	Simplified language and concrete examples	4.41 ± 0.44 (Good)
AR Interactivity	Object manipulation and system responsiveness	3.27 ± 0.52 (Fair)	Addition of rotate, zoom, and parameter features	4.53 ± 0.46 (Very Good)
Numeracy Integration	Relevance between data and context	3.05 ± 0.58 (Fair)	Inclusion of authentic <i>karapan sapi</i> data and graphical representations	4.45 ± 0.47 (Good)
Content Validity	Aiken’s V (5 experts)	0.79 (Moderately Valid)	Revision of content substance and curriculum alignment	0.87 (Valid)
Practicality (Students)	Likert score (n = 32)	76.5% ± 6.2 (Practical)	Improvements in UX, navigation, and instructions	88.6% ± 4.8 (Highly Practical)
Practicality (Teachers)	Likert score (n = 2)	78.2% ± 5.5 (Practical)	Alignment with lesson plans and instructional flow	90.1% ± 3.9 (Highly Practical)

Based on Table 3, the practicality of the AR-based SMART e-Module was categorized as very high, as reflected by the consistently strong evaluations from both students and teachers, with scores exceeding 88%. This

level of practicality was supported by the coherence across multiple aspects, including navigation, instructional clarity, and AR interactivity, as well as by the stability of the assessment reliability. Furthermore, the findings indicate direct pedagogical implications, particularly in facilitating classroom implementation, enhancing student engagement, and improving the overall effectiveness of learning activities.



Figure 6. Final Prototype of the AR-Based SMART e-Module

### 3.2. Effectiveness of Learning (Quasi-Experimental Study)

The effectiveness of the AR-based SMART e-Module was examined to determine the impact of the intervention on students' numeracy and scientific literacy skills through an inferential quantitative approach. The analysis involved prerequisite statistical tests, N-gain analysis, ANCOVA, and effect size measurement using Cohen's  $d$ . The N-gain results revealed that the AR-based SMART e-Module produced substantially greater improvements in numeracy and scientific literacy skills, with gain differences ranging from +0.27 to +0.30 compared with the control group (see Table 4).

Table 4. N-Gain Results for Numeracy and Scientific Literacy

Domain	Indicator	Group	Pretest	Posttest	N-gain	$\Delta$ Gain (Exp-Ctrl)
Numeracy	Quantitative data interpretation	Experimental	44.87	84.26	0.72	+0.28
		Control	45.13	69.34	0.44	
	Quantitative reasoning	Experimental	46.28	83.57	0.69	+0.29
		Control	45.61	68.76	0.40	
	Numerical problem-solving	Experimental	44.92	82.44	0.68	+0.30
		Control	45.08	66.91	0.38	
Data/graph representation	Experimental	45.36	83.11	0.71	+0.27	
	Control	44.94	69.02	0.43		
Scientific Literacy	Understanding scientific concepts	Experimental	45.21	84.03	0.70	+0.29
		Control	45.07	68.64	0.41	
	Analysis of scientific phenomena	Experimental	44.98	81.92	0.67	+0.29
		Control	44.86	67.58	0.38	
	Scientific inference	Experimental	45.34	80.63	0.65	+0.28
		Control	44.71	66.84	0.37	
Scientific communication	Experimental	45.18	82.36	0.69	+0.30	
	Control	44.95	68.11	0.42		

The findings presented in Table 4 indicate that the Augmented Reality (AR)-based SMART e-Module consistently generated higher learning gains than the control group across both competency domains, with N-gain differences ranging from 0.27 to 0.30. The most pronounced improvement was observed in the numeracy domain, particularly in quantitative data interpretation ( $g = 0.72$ ), suggesting that AR visualization played a substantial role in facilitating the transformation of abstract numerical information into more concrete visual-spatial representations. A comparable pattern was identified in scientific literacy, especially in the analysis of scientific phenomena and scientific inference ( $g = 0.65-0.67$ ). These findings imply that AR not only enhanced conceptual understanding but also strengthened evidence-based scientific reasoning processes. Overall, the relatively stable effect gap (approximately 0.28) across all indicators demonstrates that the AR intervention exerted a systematic and consistent impact on both numeracy and scientific literacy competencies rather than producing incidental learning improvements (see Table 5).

Table 5. Comparison of N-Gain Improvements between the Experimental and Control Groups

Domain	Indicator	Experimental Mean N-gain (SD)	Control Mean N-gain (SD)	Δ Gain (Exp-Ctrl)
Numeracy	Quantitative data interpretation	0.72 (0.08)	0.44 (0.07)	+0.28
	Quantitative reasoning	0.69 (0.09)	0.40 (0.08)	+0.29
	Numerical problem-solving	0.68 (0.10)	0.38 (0.09)	+0.30
	Data/graph representation	0.71 (0.08)	0.43 (0.08)	+0.27
Scientific Literacy	Understanding of scientific concepts	0.70 (0.09)	0.41 (0.08)	+0.29
	Analysis of scientific phenomena	0.67 (0.09)	0.38 (0.07)	+0.29
	Scientific inference	0.65 (0.10)	0.37 (0.08)	+0.28
	Scientific communication	0.69 (0.08)	0.42 (0.08)	+0.30

The findings presented in Table 5 indicate that the AR-based SMART e-Module consistently enhanced students' numeracy and scientific literacy skills more effectively than the control condition, as reflected in the higher N-gain difference ( $\Delta$  N-gain = 0.27–0.30). The strongest effects were observed in visual-representational competencies, particularly data interpretation ( $g = 0.72$ ) and graphical representation ( $g = 0.71$ ). From a theoretical perspective, these improvements can be explained through the enhancement of dual-channel processing and the reduction of cognitive load, as proposed in the Cognitive Theory of Multimedia Learning. In this context, augmented reality functioned as a transformative instructional medium that converted abstract concepts into interactive visual representations, thereby strengthening students' quantitative reasoning and scientific inference. Although the intervention demonstrated a more pronounced impact on numeracy than on scientific literacy, the results nevertheless revealed systematic and consistent improvements across all measured indicators, confirming the significant pedagogical effectiveness of the visual-spatial learning approach (see Figure 8). The results of the Shapiro–Wilk normality test indicated that both pretest and posttest scores in the experimental group ( $p = 0.112$ ;  $p = 0.087$ ) and the control group ( $p = 0.094$ ;  $p = 0.101$ ) were normally distributed ( $p > 0.05$ ). Furthermore, Levene's homogeneity test confirmed that the variance between groups was homogeneous ( $F = 1.32$ ,  $p = 0.254$ ,  $p > 0.05$ ), indicating that all fundamental assumptions required for ANCOVA were satisfactorily fulfilled. Consequently, the ANCOVA procedure was considered statistically appropriate for estimating the net effect of the instructional intervention (see Table 6).

Table 6. ANCOVA Results

Source	Sum of Squares	df	Mean Square	F	p-value	Partial $\eta^2$
Covariate (Pretest)	1123.45	1	1123.45	24.16	<0.001	0.28
Group	1389.67	1	1389.67	18.74	<0.001	0.23
Error	4521.88	61	74.12	—	—	—

Based on the ANCOVA results presented in Table 10, after controlling for students' initial abilities, the AR-based SMART e-Module intervention exerted a statistically significant effect on the improvement of numeracy and scientific literacy skills ( $F(1,61) = 18.74$ ,  $p < 0.001$ ,  $\eta^2 = 0.23$ ). This finding was further supported by the adjusted mean scores, which demonstrated that the experimental group achieved a substantially higher corrected mean score ( $M_{adj} = 82.11$ ) than the control group ( $M_{adj} = 68.34$ ). These results reinforce the effectiveness of the intervention in significantly enhancing students' learning outcomes. Moreover, the Partial  $\eta^2$  value indicated that 23% of the variance in students' achievement gains could be attributed to the intervention, representing a large effect size. Therefore, the observed differences in learning outcomes were not merely due to variations in prior ability, but were strongly associated with the implementation of the AR-based instructional approach.

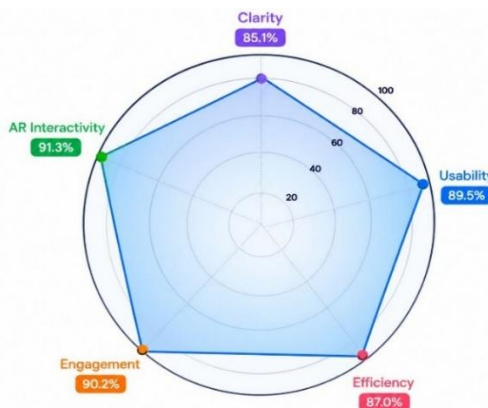


Figure 7. Practicality Profile of the AR-Based SMART e-Module

### 3.3 Student Engagement

The observation results indicated that all dimensions of student engagement were categorized as high, with mean scores of behavioral engagement ( $M = 3.50$ ), emotional engagement ( $M = 3.60$ ), and cognitive engagement ( $M = 3.70$ ). These findings were consistently supported by the operational indicators presented in Table 11, which demonstrated a structured and measurable pattern of engagement. Within the behavioral dimension, the highest scores were observed in the frequency of AR utilization for concept exploration ( $M = 3.6$ ) and participation in data-based tasks ( $M = 3.5$ ), suggesting that students' involvement was not merely passive but was actively facilitated through technology-mediated interaction and numeracy-oriented activities. In the emotional dimension, enthusiasm toward AR visualization ( $M = 3.7$ ) and interest in the ethnoscientific context of Madurese bull racing (*Karapan Sapi*) ( $M = 3.8$ ) emerged as the dominant indicators, indicating that affective engagement was stimulated through the integration of immersive technology and culturally contextualized learning experiences. Meanwhile, the cognitive dimension obtained the highest overall mean score ( $M = 3.70$ ), as reflected in students' abilities in graphical data interpretation ( $M = 3.8$ ), quantitative reasoning ( $M = 3.7$ ), and AR simulation-based inference ( $M = 3.6$ ). These findings confirm that the AR-based SMART e-Module not only enhanced students' participation and motivation, but also more substantively promoted higher-order cognitive engagement directly associated with science and numeracy literacy.

Table 7. Dimensions of student engagement

Dimension	Indicator	Mean	SD	Category
Behavioral Engagement	Frequency of participation in data-driven numerical discussions (number of responses per session)	3.40	0.52	High
	Frequency of interaction with AR features (rotation, zoom, and simulation per session)	3.60	0.48	Very High
	Accuracy in completing numeracy tasks based on experimental data (0–4 rubric scale)	3.50	0.50	Very High
	Adherence to the e-module instructional sequence ( <i>task completion rate</i> )	3.50	0.46	Very High
	Average Behavioral Engagement	3.50	0.49	Very High
Emotional Engagement	Affective responses toward AR visualizations ( <i>interest response scale</i> )	3.70	0.45	Very High
	Interest in the ethnoscience context of <i>karapan sapi</i> ( <i>contextual relevance scale</i> )	3.80	0.40	Very High
	Intrinsic motivation to complete scientific literacy tasks ( <i>self-report scale</i> )	3.50	0.51	Very High
	Self-efficacy in solving numeracy problems ( <i>confidence rating</i> )	3.40	0.53	High
Average Emotional Engagement	3.60	0.47	Very High	
Cognitive Engagement	Interpretation of data representations (position–time and velocity graphs)	3.80	0.42	Very High
	Quantitative reasoning in force–mass–acceleration models	3.70	0.44	Very High
	AR simulation-based inference ( <i>prediction accuracy score</i> )	3.60	0.46	Very High
	Analysis of scientific concepts through AR-based multimodal representations	3.70	0.43	Very High
Average Cognitive Engagement	3.70	0.44	Very High	

Based on Table 7, the high level of cognitive engagement indicates that the use of AR not only increased student participation but also causally stimulated higher-order thinking processes through the dynamic visualization of abstract concepts, such as the relationship among force, mass, and acceleration, thereby facilitating data-driven reasoning and inferential thinking. In parallel, the high level of emotional engagement suggests that the ethnoscience context of the Madurese *karapan sapi* functioned as a motivational catalyst that enhanced the perceived relevance of learning and strengthened students' intrinsic engagement. Meanwhile, the consistently high behavioral engagement reflects sustained active participation fostered by the structured and interactive instructional design. Collectively, these findings demonstrate a causal relationship in which the simultaneous integration of AR and cultural context substantially enhanced the quality of student engagement across cognitive, affective, and behavioral dimensions (see Figure 6).

### 3.4 Qualitative Analysis (Thematic Findings)

The qualitative analysis, conducted through thematic analysis and strengthened by triangulation procedures, revealed three major findings. First, the AR-based SMART e-Module enhanced students' understanding of abstract concepts through dynamic visualizations that strengthened the interpretation and

representation of motion-related phenomena. Second, the module increased students' cognitive and emotional engagement by promoting active exploration and sustained focus on numeracy tasks. Third, the integration of the Madurese *karapan sapi* cultural context reinforced the relevance of learning, thereby fostering students' scientific inference and analytical understanding of physical phenomena. The consistency between students' responses and classroom observations further confirmed these findings (see Table 8).

Table 8. Thematic Analysis Based on Numeracy and Scientific Literacy Indicators

Coding Category	Competency Indicator	Evidence	F	Alignment
AR visualization enhances understanding of dynamic concepts	Data/graph representation and scientific conceptual understanding	"I finally understood the relationship between force and motion after seeing the AR simulation" (S12)	27/32 (84%)	Consistent with the increase in N-gain ( $g = 0.72$ )
AR improves quantitative analytical skills	Quantitative reasoning and numerical problem-solving	"I could change the mass and immediately observe changes in acceleration" (S21)	24/32 (75%)	Consistent with improvements in quantitative reasoning ( $g = 0.68$ )
The <i>karapan sapi</i> context strengthens scientific inference	Scientific inference and phenomenon analysis	"The <i>karapan sapi</i> context made it easier for me to understand the concepts of force and velocity" (S14)	29/32 (91%)	Supports the improvement in scientific inference ( $g = 0.74$ )
AR increases motivation and scientific communication	Scientific communication and emotional engagement	"Learning felt like playing, but I still understood the concepts well" (S25)	26/32 (81%)	Increased participation in classroom discussions
AR promotes scientific exploratory activities	Numerical problem-solving and data interpretation	"I explored all the features independently until I understood the results" (S08)	30/32 (94%)	Supports the improvement of numeracy literacy

Based on Table 8, the effectiveness of the AR-based SMART e-Module in enhancing numeracy and scientific literacy emerged through integrated cognitive mechanisms, including cognitive load reduction, visual-verbal dual coding integration, and active exploratory learning. These mechanisms were further reinforced by the culturally contextualized *karapan sapi* phenomenon, which functioned as a catalyst for scientific inference grounded in authentic real-world experiences. These qualitative findings were consistent with classroom observations indicating increased behavioral, emotional, and cognitive engagement among students. Furthermore, the findings aligned with the observed improvements in N-gain scores across indicators of data representation, quantitative reasoning, and scientific inference. Through the triangulation of qualitative data, classroom observations, and quantitative findings, the overall validity of the study was substantially strengthened, rendering the findings not only descriptive in nature but also confirmatory and inferential (see Figure 6).



Figure 8. Visual Representation of the Traditional Madurese Bull Racing Culture (*Karapan Sapi*)

The qualitative analysis, conducted through thematic analysis and strengthened by triangulation procedures, revealed three major findings. First, the AR-based SMART e-Module enhanced students' understanding of abstract concepts through dynamic visualizations that strengthened the interpretation and representation of motion-related phenomena. Second, the module increased students' cognitive and emotional engagement by promoting active exploration and sustained focus on numeracy tasks. Third, the integration of the Madurese *karapan sapi* cultural

context reinforced the relevance of learning, thereby fostering students' scientific inference and analytical understanding of physical phenomena. The consistency between students' responses and classroom observations further confirmed these findings (see Table 8).

### 3.4 Media Usability, User Experience, and System Performance

The evaluation of media usability, user experience, and system performance was conducted to examine the technological quality and operational feasibility of the AR-based SMART e-Module during classroom implementation. The analysis focused on three major dimensions: media usability, user experience, and system performance. The findings demonstrated consistently high scores across all evaluated indicators, indicating that the AR-based learning environment was not only pedagogically effective but also technologically reliable and user-friendly for junior high school students (see Table 9).

Table 9. Media Usability, User Experience, and System Performance Evaluation

Dimension	Indicator	Mean	SD	Category
Media Usability	Ease of use	4.45	0.42	Very High
	Navigation performance	4.38	0.46	Very High
	Interaction smoothness	4.41	0.44	Very High
User Experience	Average Media Usability	4.41	0.44	Very High
	Immersive learning experience	4.52	0.40	Very High
	Media satisfaction	4.47	0.43	Very High
	Visual engagement	4.58	0.39	Very High
System Performance	Average User Experience	4.52	0.41	Very High
	System responsiveness	4.36	0.48	Very High
	AR tracking stability	4.31	0.50	Very High
	Rendering quality	4.49	0.41	Very High
	Average System Performance	4.39	0.46	Very High

Based on Table 9, the AR-based SMART e-Module demonstrated very high levels of usability, user experience, and system performance. Students reported that the system was easy to use, supported intuitive navigation, and enabled smooth interaction with AR objects ( $M = 4.38\text{--}4.45$ ), indicating that the interface effectively minimized technical complexity and allowed greater focus on conceptual exploration. The module also generated highly positive learning experiences, reflected in high scores for immersive experience, visual engagement, and media satisfaction ( $M = 4.47\text{--}4.58$ ), suggesting that the integration of AR visualization and ethnoscience contexts enhanced both cognitive and affective engagement. In addition, the application showed strong technological performance, including high responsiveness, tracking stability, and rendering quality ( $M = 4.31\text{--}4.49$ ), ensuring reliable implementation in authentic classroom settings. Overall, these findings indicate that the effectiveness of the AR-based SMART e-Module was supported not only by its instructional content but also by the quality of interaction design, immersive visualization, and technological reliability, enabling the module to function as an integrated learning environment that promotes engagement, conceptual understanding, and scientific reasoning.

The evaluation results demonstrated that the AR-based SMART e-Module achieved consistently high scores across media usability, user experience, and system performance dimensions. In terms of usability, students reported that the system was easy to operate, featured intuitive navigation, and enabled smooth interaction with AR objects. These findings indicate that the instructional interface successfully minimized operational complexity, thereby allowing students to focus more effectively on conceptual exploration rather than technical manipulation. From the user experience perspective, the high levels of immersive experience, visual engagement, and media satisfaction suggest that the AR environment created meaningful and emotionally engaging learning experiences. This immersive quality likely contributed to the sustained cognitive and behavioral engagement observed throughout the intervention. Furthermore, the system performance evaluation confirmed that the AR application demonstrated stable tracking performance, responsive interaction, and high-quality rendering, all of which are critical factors influencing the effectiveness of immersive learning environments. Collectively, these findings reinforce the argument that the pedagogical effectiveness of AR-based learning is strongly associated not only with instructional content, but also with the quality of usability, interaction design, and technological system performance.

Overall, the findings demonstrate that the AR-integrated SMART e-Module, developed through a Design-Based Research (DBR) approach, significantly improved product quality, instructional effectiveness, and student engagement. The iterative DBR process contributed to increases in validity (Aiken's  $V: 0.79\text{--}0.87$ ) and practicality (76.5%–88.6%) through continuous refinement of navigation, instructional scaffolding, and AR interactivity [89], [90]. Furthermore, students in the experimental group achieved substantially higher numeracy and scientific literacy gains ( $\Delta N\text{-gain} = +0.27\text{--}0.30$ ), supported by significant ANCOVA results ( $F(1,61) = 18.74; p < 0.001; \eta^2$

= 0.23). These findings suggest that AR functions as an immersive cognitive tool that facilitates visual-spatial representation and multimodal learning, enabling students to connect mathematical symbols with real-world scientific phenomena [76], [78]. Consistent with previous studies [70], [86], high engagement scores across behavioral, emotional, and cognitive dimensions ( $M = 3.50\text{--}3.70$ ) indicate that AR promotes active participation and efficient information processing [77], [94]. Moreover, integrating the ethnoscience context of *karapan sapi* increased learning relevance and intrinsic motivation, supporting the view that culturally contextualized instruction enhances engagement and knowledge retention [82]. Furthermore, the integration of ethnoscience contexts, such as the Madurese *karapan sapi* tradition, enhanced the contextual relevance of learning and contributed to stronger intrinsic motivation and meaningful learning experiences [56], [64]. This finding is in line with the broader literature emphasizing that culturally contextualized learning can bridge the abstraction of scientific concepts with students' lived experiences, thereby improving engagement and knowledge retention [11], [63]. The convergence of quantitative, observational, and qualitative evidence further strengthens the validity of these findings and confirms that the integration of AR and ethnoscience effectively enhances numeracy and scientific literacy through interactive, contextual, and experience-based learning mechanisms [79], [81].

The findings indicate that the AR-based SMART e-Module significantly improved students' numeracy and scientific literacy, particularly in quantitative data interpretation ( $N\text{-gain} = 0.72$ ) and data/graph representation ( $N\text{-gain} = 0.71$ ), with consistent differences between the experimental and control groups ( $\Delta = 0.27\text{--}0.30$ ). These improvements suggest that AR effectively transformed abstract scientific concepts into interactive visual-spatial representations that enhanced students' interpretative, modeling, and quantitative reasoning skills. This finding is consistent with previous studies demonstrating that AR improves conceptual understanding through dynamic visualization and interactive learning experiences [76], [77]. From a theoretical perspective, the results can be explained through the Cognitive Theory of Multimedia Learning and Cognitive Load Theory, where AR supports the integration of visual and verbal information while reducing extraneous cognitive load, thereby facilitating higher-order thinking processes such as analysis, evaluation, and inference [73], [95]. Improvements in scientific phenomenon analysis ( $g = 0.67$ ) and scientific inference ( $g = 0.65$ ) further indicate that AR functioned as a cognitive scaffold that supported evidence-based reasoning in line with the PISA scientific literacy framework [18], [25]. The ANCOVA results ( $F(1,61) = 18.74$ ;  $p < 0.001$ ;  $\eta^2 = 0.23$ ) confirm that these gains were substantial even after controlling for prior ability, suggesting that the observed improvements were attributable to the structured AR-based instructional design. Therefore, AR should be viewed not merely as a visualization tool but as an immersive learning environment that facilitates conceptual understanding, scientific reasoning, and numeracy development through interactive and experiential learning mechanisms [79], [88], [89], [94].

Furthermore, the consistent improvements in data representation ( $g = 0.71\text{--}0.72$ ), quantitative reasoning ( $g = 0.69$ ), and scientific inference ( $g = 0.65\text{--}0.67$ ) suggest that AR played a transformative role in supporting scientific knowledge construction. Through dynamic visualization and real-time interaction, AR reduced conceptual abstraction and facilitated the development of mental models and cause-and-effect reasoning, consistent with previous studies on representational learning in science and mathematics [45], [50]. These findings were reinforced by the high level of behavioral engagement observed during the intervention ( $M = 3.50$ ; 94% active exploration), indicating that students actively participated in inquiry and meaning-making processes. As active engagement is closely associated with critical thinking and scientific literacy development, [67], [96], the results support the view that AR functions as a cognitive tool that integrates visualization, interactivity, and experiential learning to enhance conceptual understanding and scientific reasoning [29], [97]. Beyond instructional effectiveness, the success of the AR-based SMART e-Module was also influenced by its technological quality. High scores in usability, immersive experience, and system responsiveness indicate that smooth navigation, stable interaction, and intuitive AR manipulation reduced technological barriers and allowed students to focus on conceptual exploration. This finding is consistent with previous research emphasizing that the effectiveness of immersive learning environments depends not only on instructional content but also on interface usability and system reliability [84], [85]. Indeed, meta-analytic studies have shown that, in the absence of appropriate instructional design, AR implementation may impose additional cognitive load that ultimately hinders learning outcomes [76], [77]. Therefore, technological quality should be regarded as an integral pedagogical component in the design of AR-supported learning environments.

Based on the findings from Cycle I, a data-driven revision process was conducted, including interface simplification, improved navigation, enhanced AR interactivity, and the integration of the Madurese *karapan sapi* ethnoscience context. These revisions were intended to reduce cognitive load, strengthen representational connections, and increase the contextual relevance of learning [56], [64]. As a result, Cycle II demonstrated substantial improvements in product quality, with validity increasing from 0.79 to 0.87 and practicality from 76.5% to 88.6%. Notably, AR interactivity improved from 3.27 to 4.53, while numeracy integration increased from 3.05 to 4.45, indicating that the revisions enhanced both learning interaction quality and students' cognitive engagement. These findings support previous studies suggesting that the effectiveness of AR-based learning depends on instructional designs that promote active exploration and meaningful conceptual engagement [73], [94]. Furthermore, the results confirm the value of DBR as an iterative framework that systematically aligns

instructional design with learners' cognitive needs through evidence-based refinement [88], [98]. Therefore, the integration of AR and ethnoscience should be viewed not merely as a technological enhancement but as a pedagogical strategy capable of supporting higher-order thinking, numeracy development, and contextual STEM learning [29], [70].

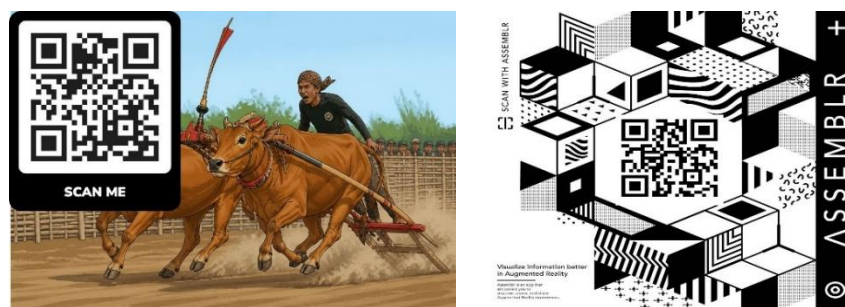


Figure 8. Screenshot of the AR Feature

Student engagement in the AR-based SMART e-Module was categorized as high across behavioral, emotional, and cognitive dimensions ( $M = 3.50\text{--}3.70$ ). The high level of active participation (94%) suggests that AR facilitated learning through real-time interaction, immediate feedback, and immersive exploration, transforming students from passive recipients into active learners [77], [99]. Emotional engagement was further strengthened by the integration of the Madurese *karapan sapi* ethnoscience context, which increased the relevance and meaningfulness of learning experiences [56], [63], [64]. Similarly, strong cognitive engagement in data interpretation, quantitative reasoning, and scientific inference indicates that AR functioned as a cognitive tool that reduced abstraction through dynamic visualization and representational scaffolding [45], [79], [100]. The consistency between observational, questionnaire, and achievement data suggests that technological interactivity, cultural contextualization, and exploratory learning jointly contributed to the enhancement of students' engagement and higher-order thinking skills [1], [101], [102].

The convergence of quantitative (N-gain and ANCOVA), qualitative, and observational findings demonstrates that improvements in numeracy and scientific literacy were not isolated outcomes but resulted from a coherent instructional mechanism integrating AR visualization, interactivity, and ethnoscience-based learning. Consistent with the Cognitive Theory of Multimedia Learning and Cognitive Load Theory, AR supported dual-channel processing while reducing cognitive burden, enabling students to construct deeper conceptual understanding and scientific reasoning [77], [103]. Furthermore, the integration of local cultural contexts strengthened knowledge construction and scientific inference by connecting scientific concepts with students' lived experiences [56], [59], [63]. These findings reinforce the view that AR should be understood not merely as a visualization tool but as an immersive cognitive learning environment that promotes engagement, reasoning, and scientific literacy development [25], [29].

A key novelty of this study lies in the development and empirical validation of an AR-based SMART e-Module that systematically integrates Augmented Reality, ethnoscience contextualization, and numeracy-scientific literacy instruction within a Design-Based Research (DBR) framework. While previous studies have generally examined AR, ethnoscience, or literacy development as separate instructional components, limited research has investigated how these elements operate simultaneously within a single iterative learning ecosystem. Furthermore, most AR studies have primarily focused on learning achievement or motivation outcomes, with relatively little attention given to the integrated relationships among technological usability, student engagement, instructional refinement, and literacy development. By combining immersive AR visualization, the local cultural context of *karapan sapi*, and iterative DBR cycles, this study proposes a comprehensive pedagogical model that explains how technological interaction, cultural relevance, and cognitive engagement collectively contribute to improvements in numeracy and scientific literacy. Therefore, the contribution of this study extends beyond evaluating the effectiveness of AR technology, offering a theoretically grounded framework that positions AR as an integrated cognitive-cultural learning ecosystem capable of supporting twenty-first-century competencies.

The findings suggest that AR implementation in science education should move beyond technology-centered approaches toward pedagogically and culturally contextualized designs. Educators are encouraged to integrate local knowledge systems and ethnoscience contexts into AR learning environments to enhance relevance, engagement, and literacy development. For instructional designers, the results highlight the importance of usability, interaction quality, and iterative refinement processes in maximizing the educational impact of immersive technologies. This study extends the Cognitive Theory of Multimedia Learning and Cognitive Load Theory by demonstrating that AR functions not only as a visualization tool but also as a cognitive-cultural mediator that facilitates knowledge construction through the interaction of technological immersion, contextual relevance, and learner engagement. The findings further contribute to the growing literature on AR-enhanced learning by

proposing the concept of an integrated cognitive-learning ecosystem in which technological, cultural, and pedagogical components operate synergistically to promote scientific literacy and numeracy development.

Despite its contributions, this study has several limitations. First, the intervention was conducted within a single educational context and involved a relatively limited sample, which may restrict the generalizability of the findings. Second, the study focused on short-term learning outcomes and did not examine the long-term retention of numeracy and scientific literacy skills. Third, the AR application employed a marker-based system and was implemented in a specific ethnoscience context (*karapan sapi*), which may influence its applicability in different cultural settings. Future studies should involve larger and more diverse samples, investigate long-term learning retention, compare different AR interaction models, and explore the integration of various local cultural contexts to further validate and extend the proposed cognitive-cultural learning ecosystem framework.

#### 4. CONCLUSION

This study concludes that the AR-based SMART e-Module integrated with the ethnoscience context of Madurese *karapan sapi* is a valid, practical, and effective learning innovation for improving students' numeracy and scientific literacy. Developed through an iterative Design-Based Research (DBR) approach, the e-Module demonstrated significant improvements in product quality, instructional effectiveness, and student engagement. The findings showed that students who learned using the AR-based SMART e-Module achieved higher gains in numeracy and scientific literacy, accompanied by high levels of behavioral, emotional, and cognitive engagement. These results indicate that the integration of immersive AR visualization, interactive learning experiences, and culturally relevant contexts can facilitate meaningful knowledge construction, strengthen scientific reasoning, and support higher-order thinking processes. The study contributes theoretically by positioning AR as a cognitive-cultural learning environment that mediates the relationship between visualization, engagement, and literacy development. Practically, the findings provide evidence that culturally contextualized AR learning environments can serve as effective alternatives for supporting twenty-first-century competencies in science education. The novelty of this study lies in the integration of Augmented Reality, ethnoscience contextualization, and iterative DBR refinement within a unified learning ecosystem that simultaneously enhances learning quality, engagement, and literacy outcomes.

Despite these contributions, the study was conducted within a single cultural context and over a relatively short intervention period. Therefore, future research should examine the long-term impact of AR-based learning, involve more diverse educational settings, and explore the integration of adaptive technologies such as artificial intelligence and learning analytics to further personalize and optimize immersive learning experiences.

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#### AUTHOR CONTRIBUTIONS

Conceptualization, Andri Imam Subekhi and Nandang Kusmana; Methodology, Andri Imam Subekhi, Bagus Ardi Saputro, and Yusup Junaedi; Software, Bagus Ardi Saputro; Validation, Nandang Kusmana, Yusup Junaedi, and Teguh Ardianto; Formal Analysis, Andri Imam Subekhi and Yusup Junaedi; Investigation, Andri Imam Subekhi and Teguh Ardianto; Resources, Nandang Kusmana; Data Curation, Bagus Ardi Saputro; Writing – Original Draft Preparation, Andri Imam Subekhi; Writing – Review & Editing, Nandang Kusmana, Bagus Ardi Saputro, Yusup Junaedi, and Teguh Ardianto; Visualization, Bagus Ardi Saputro; Supervision, Nandang Kusmana and Teguh Ardianto; Project Administration, Andri Imam Subekhi; Funding Acquisition, Nandang Kusmana.

#### INFORMED CONSENT STATEMENT

Informed consent was obtained from all participants involved in this study. Prior to participation, each participant was provided with a comprehensive explanation regarding the objectives of the study, research procedures, potential risks and benefits, as well as the confidentiality and voluntary nature of participation. All participants voluntarily agreed to participate and provided written informed consent before the data collection process commenced.

## CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this article. The authors confirm that the research was conducted in the absence of any commercial, financial, or personal relationships that could be construed as potential conflicts of interest. Furthermore, the funding sponsors had no role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

## USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

Not applicable

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