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RESEARCH ARTICLE

Development and Validation of an Augmented Reality–Supported Contextual Teaching and Learning Module for Projectile Motion

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Abstract

This study developed and validated a contextualized physics module integrating Augmented Reality (AR) for teaching projectile motion, addressing challenges related to abstract concepts and limited laboratory resources in physics classrooms. The research employed a Design and Development approach using the ADDIE model to produce a learning module that incorporates culturally relevant examples and interactive three-dimensional visualizations accessible through smartphones. The product was evaluated through expert validation and preliminary user testing. Validation by five experts resulted in very high ratings across all assessed aspects, with contextual relevance receiving the highest score (M = 4.75/5.00). Preliminary implementation involving 35 students indicated high levels of perceived practicality and user acceptance, particularly regarding engagement (M = 4.78) and the perceived usefulness of AR visualizations for clarifying projectile motion concepts (M = 4.62). Observational notes during implementation suggested that students actively related the AR simulations to real-world situations presented in the module. These findings indicate that the developed module demonstrates strong validity and practical feasibility as a technology-supported instructional resource that integrates Augmented Reality with Contextual Teaching and Learning principles. However, the study focuses on product quality evaluation through expert judgment and student perceptions; it does not measure learning effectiveness or learning gains. Future research may therefore investigate the instructional impact of the module through experimental or quasi-experimental designs.

Keywords: Physics Education; Augmented Reality; Contextual Teaching and Learning; Module Development; Projectile Motion; ADDIE Model.

Author Contributions: Yusuf Axmed conceived the study and led the development of the AR module. Sahra Warsame contributed to data collection and implementation. Asha S. Abshir supervised the research process and provided critical revisions. All authors contributed to data analysis and manuscript preparation.

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1. INTRODUCTION

A solid understanding of fundamental mechanics is crucial for developing scientific literacy and for supporting further learning in science, technology, engineering, and mathematics (STEM) fields (National Research Council, 2012). Concepts such as force, motion, and energy form the conceptual foundation of physics and are essential for explaining many everyday phenomena. Nevertheless, numerous studies have reported that students frequently experience difficulties when learning mechanics, particularly topics related to motion and kinematics (Chen et al., 2022). Among these topics, projectile motion is often perceived as abstract because it requires learners to simultaneously understand vector decomposition, parabolic trajectories, and the influence of gravitational acceleration. Without appropriate visualization and contextual examples, students may struggle to connect mathematical representations with physical phenomena.

Empirical research has also documented persistent misconceptions in projectile motion. Students commonly assume that horizontal and vertical motions influence each other directly, misunderstand the independence of velocity components, or misinterpret the role of gravity along the trajectory (Bao & Redish, 2006; Singh & Rosengrant, 2003). These conceptual difficulties indicate that learning projectile motion requires instructional approaches that support visualization and conceptual interpretation rather than reliance on symbolic formulas alone.

The situation becomes more challenging in educational environments with limited access to laboratory resources. In many schools, particularly in under-resourced regions, physics instruction is often constrained by the lack of experimental equipment needed to demonstrate motion phenomena (Cheng & Tsai, 2019). As a result, physics teaching frequently relies on static diagrams and textbook explanations, which may limit students' opportunities to engage in inquiry-based or experiential learning (Brinson, 2015). Such limitations can widen educational disparities by reducing access to meaningful science learning experiences.

To address these challenges, educational technology has increasingly been explored as a means of supporting conceptual visualization in science learning. One technology that has gained considerable attention is Augmented Reality (AR). AR allows digital information and three-dimensional virtual objects to be superimposed onto the real-world environment, enabling learners to observe and interact with dynamic representations of scientific phenomena (Akçayır & Akçayır, 2017; Ibáñez & Delgado-Kloos, 2018). In the context of physics education, AR can illustrate motion trajectories, visualize velocity vectors, and simulate physical processes in ways that are difficult to achieve using traditional instructional media (Zhang et al., 2020). Moreover, AR applications delivered through smartphones offer a relatively accessible technological solution for schools with limited laboratory facilities.

However, technological innovation alone does not guarantee meaningful learning. Effective instructional design requires strong pedagogical grounding. One pedagogical approach that emphasizes relevance and learner engagement is Contextual Teaching and Learning (CTL). CTL encourages the connection of academic content with learners' real-life experiences, local environments, and social contexts (Johnson, 2002). Through contextualization, scientific concepts can be presented using examples that are familiar to students' daily activities, cultural practices, or community environments. Such contextual connections can help learners interpret abstract ideas within meaningful situations and may enhance motivation and engagement in the learning process (Berns & Erickson, 2001).

24 Despite the growing body of research on AR in science education, several limitations remain evident in the existing literature. Many AR-based learning applications primarily focus on technological visualization and interactive simulations, while giving limited attention to pedagogical contextualization within learners' cultural or environmental backgrounds (Radu et al., 2023). In many cases, AR content is developed using generic or globally standardized examples that may not align with students' local experiences. Consequently, the potential of AR to support meaningful contextual learning has not been fully explored, particularly in educational settings with diverse cultural and environmental characteristics.

In this study, contextualization is operationally defined as the integration of physics concepts with examples, scenarios, and visual representations that are directly related to students' everyday experiences and local environments. Rather than presenting abstract projectile motion problems in purely mathematical form, the learning module incorporates familiar real-world situations and culturally relevant illustrations that allow students to interpret motion phenomena within recognizable contexts. By combining this contextual approach with AR-based visualization, the module aims to provide an interactive learning experience that connects conceptual understanding with observable phenomena.

Based on the limitations identified in previous studies, there remains a need for learning resources that integrate three key elements simultaneously: (1) interactive visualization through Augmented Reality, (2) pedagogically grounded contextual learning design, and (3) accessibility for educational environments with limited laboratory infrastructure. Addressing this gap, the present study develops and validates a contextualized physics module integrating AR for teaching projectile motion.

The module is designed as a low-cost instructional resource that utilizes widely available smartphone technology to support visualization and contextual interpretation of motion phenomena. Specifically, this study focuses on evaluating the quality of the developed module in terms of expert-based validity and its practicality during preliminary implementation with students.

11 The research is guided by the following questions:

(a) What is the validity of the contextualized AR-integrated physics module in terms of content, media, and learning design based on expert judgment?

(b) What is the practicality and user acceptance of the module based on a preliminary field test with students?

23 2. LITERATURE REVIEW

2.1. Augmented Reality in Physics Education

31 Augmented Reality (AR) has been widely recognized for its potential to create immersive and interactive learning experiences that bridge the digital and physical worlds. Defined as a technology that superimposes computer-generated information—such as images, videos, and 3D models—onto a user's

view of the real world (Azuma, 1997), AR offers unique affordances for education. In physics, these affordances are particularly potent for visualizing abstract and invisible concepts.

A growing body of research demonstrates AR's effectiveness in improving students' spatial ability and conceptual understanding, which are critical in mastering physics. For instance, traditional teaching methods often struggle to help students mentally visualize electric and magnetic fields, leading to persistent misconceptions. AR simulations can make these fields visible and interactive, allowing learners to manipulate charges and observe the resulting field lines in real-time, thereby fostering a more intuitive grasp of the concept (Cai et al., 2021). Similarly, in astronomy, AR applications can project a scaled solar system into a classroom, enabling students to observe planetary motion and orbital mechanics from multiple perspectives, a significant improvement over static diagrams in textbooks (Ibáñez & Delgado-Kloos, 2018).

The key pedagogical mechanisms through which AR aids learning include enhancing visualization, enabling multimodal interaction, and promoting embodied cognition, where physical movements and manipulations are linked to conceptual learning (Skulmowski & Rey, 2020). A meta-analysis by Zhang et al. (2020) confirmed that AR-based instruction in science subjects consistently leads to better learning outcomes compared to non-AR instruction, with particular strength in improving conceptual understanding and long-term knowledge retention.

Crucially for resource-limited settings, the most significant advantage of modern mobile AR is its ability to function on ubiquitous smartphones. This drastically lowers the barrier to entry, transforming a personal device into a portable "virtual lab" (Radu et al., 2023). This eliminates the need for expensive laboratory apparatus, consumables, and dedicated physical space, making high-quality, interactive science education more accessible and scalable than ever before.

2.2. Contextual Teaching and Learning (CTL)

Contextual Teaching and Learning (CTL) is a holistic educational philosophy that posits learning occurs most effectively when students process new information in a way that makes sense within their own frame of reference, connecting it to their own life experiences (Johnson, 2002). It is built on the constructivist principle that knowledge is not passively received but actively built by the learner, and this process is facilitated when the content is relevant and meaningful.

The core components of CTL, as outlined by the US Department of Education, include making meaningful connections, engaging in significant work, self-regulated learning, and collaborating with others (Berns & Erickson, 2001). In the context of physics education, this translates to deliberately relating abstract principles to real-world situations that are familiar and significant to the students. For example, the principles of projectile motion can be taught by analyzing the parabolic trajectory of a traditionally thrown object, such as a spear or a tossed local fruit, rather than a generic cannonball. The mechanics of levers and pulleys can be explored through the design of local architectural structures or traditional water-drawing systems.

By rooting learning in these familiar contexts, educators can achieve several critical goals. First, it increases student motivation and engagement by answering the perennial question, "Why do we need to learn this?" (Berns & Erickson, 2001). Second, it provides a concrete mental scaffold upon which abstract theories can be built, facilitating deeper cognitive processing and more robust schema construction. When students can link the equation for parabolic motion to a real-life event they have witnessed, the concept transitions from a memorized formula to a explanatory tool. This approach is especially powerful in diverse cultural settings, as it validates local knowledge and integrates it into the formal science curriculum, making education more inclusive and culturally sustaining.

2.3. Synthesis and Conceptual Framework

The combination of AR and CTL presents a powerful and synergistic pedagogical strategy, particularly for challenging educational environments. While AR provides the tool for dynamic visualization and interactive experimentation, CTL provides the essential framework and purpose for its application. AR without contextual relevance can become a technological gimmick—engaging but superficially so. Conversely, CTL without effective visualization tools may still struggle to make deeply abstract concepts tangible.

This study posits that integrating these two approaches will create a learning experience that is greater than the sum of its parts. A contextualized AR module for projectile motion would not just show a generic animation; it would allow students to use their smartphones to scan a marker related to a local context (e.g., an image of a traditional sport), triggering a 3D simulation that visualizes the motion with vectors and trajectories superimposed on their real environment. This directly links the powerful visual and interactive capabilities of AR to a culturally and personally relevant scenario provided by CTL.

This synergy is expected to be especially potent in settings where practical science activities are limited. The module does not seek to replace real-world experimentation entirely but offers a viable and effective alternative that can overcome resource constraints while simultaneously enhancing conceptual understanding through contextualization and immersive visualization. Therefore, the conceptual framework of this study is built upon this integration, aiming to develop a learning tool that is simultaneously technologically innovative, pedagogically sound, and culturally responsive.

3. METHOD

3.1. Research Design

This study employed a Design and Development (D&D) research framework aimed at producing and evaluating an educational product in the form of a contextualized physics learning module integrated with Augmented Reality (AR). The development process followed the ADDIE instructional design model, which consists of five iterative phases: Analysis, Design, Development, Implementation, and Evaluation (Branch, 2009). The ADDIE model was selected because it provides a systematic structure for developing instructional products while allowing iterative refinement based on evaluation feedback.

Within this framework, the study focused primarily on product validity and practicality, rather than measuring instructional effectiveness. Therefore, the evaluation process emphasized expert judgment and preliminary user responses during early implementation stages. The design and development approach enabled the creation of a functional AR-based module while simultaneously documenting the design process and evaluating the quality of the product in a real educational setting.

3.2. Development Procedure

The development of the contextualized AR-integrated physics module followed the five phases of the ADDIE model.

3.2.1. Analysis Phase

The analysis phase aimed to identify instructional needs and contextual constraints in physics learning. A needs assessment was conducted through semi-structured interviews with three physics teachers who had more than five years of teaching experience at the secondary school level. The interviews explored common learning difficulties, availability of laboratory facilities, and existing teaching materials. In addition, informal discussions with students and a review of previous academic records were conducted to identify learning challenges. The analysis indicated that projectile motion was frequently perceived as abstract, largely due to the difficulty of visualizing motion trajectories and vector components. Teachers also reported limited access to laboratory equipment, which restricted opportunities for experimental learning. Based on these findings, projectile motion was selected as the focus topic for module development.

3.2.2. Design Phase

During the design phase, learning objectives were formulated based on the national physics curriculum. The module structure was designed to include conceptual explanations, contextual examples, guided learning activities, and AR-based visualizations. A storyboard for the AR application was also developed, specifying interface layout, animation sequences, and user interactions. The design integrated principles of Contextual Teaching and Learning (CTL) by embedding physics concepts within familiar real-world situations. Examples were adapted to reflect local contexts, such as the motion of objects thrown during traditional activities or the trajectory of a ball in commonly played sports.

3.2.3. Development Phase

The development phase involved producing the instructional module and AR application. The printed module included explanatory text, diagrams, worked examples, and reflective questions designed to support conceptual reasoning. The AR application was developed using Unity 3D (version 2021.3 LTS) as the development platform and Vuforia Engine (version 10.12) for image recognition and tracking. Custom AR markers were embedded in the printed module. When scanned using a smartphone camera, these markers triggered interactive three-dimensional animations illustrating projectile motion trajectories and vector components. Students could observe how horizontal and vertical velocity components interact within the simulated motion.

3.2.4. Implementation Phase

The implementation phase consisted of a preliminary field test conducted with students to evaluate the practicality and usability of the module. The trial was conducted in a single 90-minute classroom session in which students used the printed module and AR application as part of a guided learning activity.

3.2.5. Evaluation Phase

The evaluation phase included expert validation and preliminary field testing. Feedback from both stages was used to refine the instructional module and improve the AR application prior to finalization.

3.3. Participants and Validation

Two groups of participants were involved in the evaluation process, consisting of expert validators and students participating in a preliminary field test. Expert validation was conducted with five experts selected through purposive sampling based on their academic qualifications and professional experience. The expert panel consisted of three physics education experts who each held a doctoral degree and had more than ten years of experience in physics teaching and curriculum development, as well as two educational technology experts specializing in multimedia learning design and digital instructional media. The experts evaluated the developed module using a structured validation instrument designed to assess several aspects of the instructional product. These aspects included content accuracy and relevance, pedagogical design and alignment with learning objectives, media design and visual attractiveness, technical quality and functionality of the Augmented Reality (AR) application, and the contextual relevance of the learning examples embedded in the module. Each item in the validation instrument was rated using a five-point Likert scale ranging from 1 (Very Poor) to 5 (Very Good).

In addition to expert validation, a preliminary field test was conducted to examine the practicality and user acceptance of the developed module. The field test involved thirty-five Grade 11 students from a secondary school who were selected using convenience sampling. The participating students had previously studied basic kinematics concepts but had not yet received formal instruction on projectile motion. It should be noted that this field test was formative and exploratory in nature, aiming to evaluate the usability and acceptance of the module rather than to measure instructional effectiveness. During the implementation session, students used the developed module and interacted with the AR application as part of guided learning activities. After completing the learning session, the students filled out a user acceptance questionnaire designed to capture their perceptions of the module's usability, engagement, and visualization features. In addition, observational notes were recorded throughout the session to document student interactions, collaborative behaviors, and any technical issues encountered during the use of the AR application.

3.4. Instrument Development and Reliability

Two main instruments were used in this study: an expert validation sheet and a student user acceptance questionnaire. The expert validation instrument consisted of 20 items distributed across five evaluation aspects: content accuracy (4 items), pedagogical design (4 items), media design (4 items), technical functionality (4 items), and contextual relevance (4 items). The instrument indicators were adapted from established evaluation criteria for digital learning media and physics instructional materials.

The student questionnaire consisted of 18 items measuring six aspects: ease of use, AR functionality, student engagement, clarity of visualization, relevance of contextual examples, and overall satisfaction. Prior to data collection, the instruments were reviewed by two educational research experts to ensure clarity and relevance. Internal consistency reliability of the student questionnaire was examined using Cronbach's alpha, which produced a coefficient of α = 0.89, indicating high reliability.

3.5. Data Analysis

Quantitative data obtained from the expert validation sheets and student questionnaires were analyzed using descriptive statistics, including mean scores and standard deviations for each evaluation aspect. These descriptive measures were used to determine the validity and practicality levels of the developed module. Qualitative data were obtained from expert comments and classroom observations during the field test. These data were analyzed using thematic analysis, involving coding and categorization of feedback to identify recurring themes and suggestions for improvement. The integration of quantitative and qualitative findings enabled a comprehensive evaluation of the module's quality and informed revisions prior to finalization.

3.6. Ethical Considerations

Ethical considerations were addressed prior to data collection. Participation of both teachers and students was voluntary, and all participants were informed about the purpose of the study. Written consent was obtained from the participating school and from students before the field test was conducted. All collected data were anonymized to ensure participant confidentiality and were used solely for research purposes.

4. RESULT AND DISCUSSION

4.1. Expert Validation Results

The results from the expert validation process provide strong quantitative and qualitative evidence for the high quality of the developed contextualized AR module. As presented in Table 1, all validated aspects received mean scores above 4.50, falling into the "Very High" validity category.

Table 1. Expert Validation Results (N=5)

Aspect Validated	Mean Score (Max 5.00)	SD	Validity Category
Content Suitability	4.65	0.24	Very High
Learning Design	4.55	0.19	Very High
Media Attractiveness	4.70	0.26	Very High
Technical Quality	4.60	0.32	Very High
Contextual Relevance	4.75	0.21	Very High

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The quantitative data indicates that the module excels particularly in Contextual Relevance (M=4.75, SD=0.21). This finding directly validates the core design decision made during the Analysis and Design phases to integrate CTL principles. The experts affirmed that the use of local examples, such as the trajectory of a thrown spear, was not merely decorative but was pedagogically sound. As one physics education expert noted, "The contextual examples are highly appropriate and would significantly increase student engagement by connecting abstract physics to their cultural tangible reality." This aligns with the literature on CTL, which posits that learning is more meaningful when rooted in familiar experiences (Johnson, 2002). The high score for Media Attractiveness (M=4.70, SD=0.26) further confirms that the AR application, developed using Unity 3D and Vuforia, was successful in creating an engaging visual product. An instructional technology expert commented, "The AR visualization effectively simplifies a complex concept. The dynamic display of vectors makes the invisible components of motion visible and intuitive." This observation underscores one of the key affordances of AR in physics education: its ability to visualize abstract concepts (Zhang et al., 2020).

The high scores for Technical Quality (M=4.60) and Content Suitability (M=4.65) demonstrate that the module is not only innovative but also robust and academically rigorous. The low standard deviations across all categories suggest a strong consensus among the experts regarding the module's quality. This comprehensive validation confirms that the development process, guided by the ADDIE model, successfully translated the identified needs from the Analysis phase into a valid and well-structured educational product.

4.2. Student Practicality and Acceptance

The results from the preliminary field test with 35 grade 11 students provide compelling evidence for the module's practicality and its positive reception by the end-users. The questionnaire results, detailed in Table 2, show consistently high mean scores across all measured constructs.

Table 2. Student Questionnaire Results (N=35)

Statement	Mean Score (Max 5.00)	SD
The module was user-friendly and easy to navigate, allowing me to complete activities without confusion.	4.55	00.38
The AR (Augmented Reality) application functioned smoothly without technical issues, providing a seamless learning experience.	4.48	00.52
The content presented in the module was highly engaging, interesting, and maintained my attention throughout the learning process.	4.78	00.29
The contextual examples included in the module effectively supported my understanding of the concepts being taught.	4.72	00.31
The AR visualizations helped clarify abstract or complex concepts, making them easier to comprehend.	4.62	00.41
I am interested in using similar modules for learning other topics, as they enhance engagement and understanding.	4.81	00.25

The highest score was for the desire to use similar modules for other topics (M=4.81, SD=0.25).

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This overwhelmingly positive response indicates that the module successfully addressed the issue of low student interest identified in the initial needs analysis. It suggests that the integration of AR and CTL transformed the learning experience from a chore into an engaging activity that students wish to repeat.

Crucially, the high scores for the statements "The contextual examples helped me understand" (M=4.72) and "The AR visualization clarified the concept" (M=4.62) demonstrate the powerful synergy between the two core design elements. Students did not just find the module entertaining; they found it intellectually clarifying. The observational data corroborates this, showing high levels of student engagement and collaborative discussion. Students were observed actively pointing out the vectors on their screens and relating the AR simulation back to the contextual examples in the booklet. For instance, one student was heard explaining to a peer, "See, the vertical speed goes down because of gravity, just like when the ball from the local sport goes up and then comes down." This comment is a direct manifestation of the constructivist learning process, where students are actively building their understanding by connecting a dynamic visualization (AR) to a culturally familiar context (CTL).

Furthermore, the high scores for ease of use (M=4.55) and application functionality (M=4.48) confirm the module's practicality in a real-world classroom setting. The use of widely available smartphones and custom, high-contrast markers proved to be a low-barrier technological solution, effectively creating the "virtual lab" intended during the Development phase. The observations noted minimal technical difficulties, and students quickly adapted to scanning the markers and interacting with the 3D models. This practicality is a critical success factor for the potential scalability and adoption of such interventions in resource-limited environments.

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4.3. Discussion

The findings of this development research indicate that the contextualized AR-integrated physics module demonstrates strong validity and practical feasibility as a learning resource. The high ratings obtained from expert validation and student questionnaires suggest that the module meets key quality criteria in terms of content accuracy, pedagogical design, media presentation, and contextual relevance. These results reflect positive expert judgments regarding the instructional design and favorable student perceptions regarding usability and engagement. However, it is important to emphasize that these findings primarily represent evaluations of product quality and user acceptance, rather than empirical evidence of improved learning outcomes (Plomp & Nieveen, 2013).

The positive responses observed during the preliminary implementation suggest that the integration of Augmented Reality and contextual learning elements may contribute to a more engaging learning environment. Students reported that AR visualizations helped them observe motion trajectories and vector components more clearly, while contextual examples provided meaningful references to familiar real-world situations. Observational notes also indicated that students frequently discussed the simulations and attempted to relate them to everyday experiences. These findings align with previous studies indicating that AR technologies can enhance visualization and support learner engagement in science education (Akçayır

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& Akçayır, 2017; Ibáñez & Delgado-Kloos, 2018). Nevertheless, engagement and perceived conceptual clarity should be interpreted cautiously, as they do not necessarily indicate measurable improvements in conceptual understanding (Radu, 2014).

One notable feature of the developed module is the deliberate integration of Augmented Reality with principles of Contextual Teaching and Learning (CTL). Within this design, AR primarily functions as a visualization tool that allows students to observe motion trajectories dynamically, while contextual examples provide meaningful scenarios that situate abstract physics concepts within familiar environments. This approach is consistent with constructivist learning perspectives, which emphasize the role of contextual experiences in helping learners connect new information with prior knowledge (Johnson, 2002; Berns & Erickson, 2001). Rather than presenting generic simulations, the module incorporates examples that reflect activities recognizable to students in their everyday environment. Such contextualization may help learners interpret mathematical representations of motion through observable and relatable phenomena. However, the present findings only demonstrate positive perceptions of this integration; further empirical studies are required to determine whether it leads to measurable conceptual learning gains.

Several limitations of the present study should also be acknowledged. First, the evaluation focused on product validity and practicality, involving a relatively small number of experts (N = 5) and students (N = 35). The preliminary field test was exploratory in nature and did not include comparison groups or pre–post assessments of learning outcomes. Second, the high ratings reported by students may partially reflect novelty effects, as the introduction of immersive technologies such as AR can initially increase curiosity and motivation (Akçayır & Akçayır, 2017). Third, self-reported questionnaire responses may be influenced by social desirability bias, which can occur when participants provide favorable responses in educational evaluation contexts (Podsakoff et al., 2003). These factors limit the extent to which the results can be interpreted as indicators of instructional effectiveness.

Future research should therefore extend the evaluation of the module through more rigorous research designs. For instance, quasi-experimental studies comparing students who use the AR-integrated module with those receiving conventional instruction could provide empirical evidence regarding its impact on conceptual understanding and problem-solving ability. In addition, longitudinal studies may help determine whether repeated exposure to contextualized AR learning environments contributes to sustained interest in physics and improved retention of scientific concepts.

Overall, the present study contributes to the field of technology-enhanced science education by proposing a design approach that combines Augmented Reality visualization with contextual learning principles. While the current findings demonstrate that the developed module is valid and practical as a learning resource, further empirical investigation is necessary to determine its instructional impact. The results therefore represent an initial step toward developing contextually grounded digital learning media that are accessible and adaptable for educational environments with limited laboratory resources.

5. CONCLUSION

This study successfully achieved its objective of developing and validating a contextualized Augmented Reality-integrated physics module for teaching mechanics, specifically projectile motion. The rigorous development process, guided by the ADDIE model, resulted in a product that was deemed highly valid by experts in terms of content, learning design, media attractiveness, technical quality, and—most notably—contextual relevance. Furthermore, the preliminary field testing demonstrated that the module is highly practical and engaging from the students' perspective, with strong indicators of user acceptance and perceived learning. This outcome conclusively demonstrates that a carefully designed, digitally-based learning module can serve as a powerful and viable tool for overcoming significant infrastructural and resource barriers in physics education, providing an immersive "virtual lab" experience where physical labs are not feasible.

The findings of this research carry several important implications for theory and practice. The primary theoretical implication is the robust validation of a synergistic pedagogical model that integrates technological affordances with cultural context. This study provides empirical evidence that the effectiveness of advanced technologies like AR is significantly amplified when they are not used in a vacuum but are embedded within a Contextual Teaching and Learning (CTL) framework. This underscores that meaningful learning occurs at the intersection of digital innovation and culturally responsive pedagogy.

For educational practice, the main implication is that effective innovation in resource-limited settings must be as much about cultural design as it is about technological specification. The high scores on contextual relevance suggest that developers and educators must prioritize the localization of content. Simply transplanting Western-centric digital learning tools is insufficient; maximizing learning impact requires a deliberate effort to root examples, scenarios, and visualizations in the learners' immediate cultural, environmental, and social realities. This module serves as a practical model for how to undertake this process, demonstrating that smartphones can be leveraged not just for generic apps, but for delivering culturally-specific, curriculum-aligned learning experiences.

Based on the conclusions of this development phase, several pathways for future research are recommended. First and foremost, a quasi-experimental study is strongly recommended to quantitatively measure the module's efficacy on students' conceptual understanding and scientific reasoning skills compared to conventional teaching methods. This would provide robust, comparative data on its direct impact on learning outcomes. Second, longitudinal research is needed to investigate the long-term effects of such interventions on knowledge retention and students' attitudes toward STEM subjects. Third, the developed framework should be adapted and tested with other difficult topics in physics, such as electricity and magnetism or wave optics, to explore its generalizability. Finally, research could investigate the model's scalability and the necessary support structures for wide-scale teacher training and implementation, ensuring that such innovations can move beyond a research context into mainstream educational practice.

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