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Research Article

IMPLEMENTATION OF AUGMENTED REALITY (AR) FOR REMOTE SCIENCE LABORATORY PRACTICUMS: A SOLUTION FOR EQUIPMENT SCARCITY IN SECONDARY SCHOOLS

Lindawati[1], Devi Anggi Friani[2], Daiki Nishida[3]
[1] Institut Pesantren Babakan Cirebon, Indonesia
[2] Universitas Doktor Nugroho Magetan, Indonesia
[3] Chuo University, Japan

Corresponding Author:

Lindawati,
Sharia Economic Law, Faculty of Sharia, Institut Pesantren Babakan Cirebon.
Jl. KH. Masduqi Ali Blok Kasab, Babakan, Kecamatan Ciwaringin, Kabupaten Cirebon, Jawa Barat, Indonesia
Email: lindawati9833@gmail.com

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Abstract

Scarcity of adequate laboratory equipment in many secondary schools poses a significant barrier to effective science education, hindering students' ability to gain hands-on experimental skills. While virtual labs exist, they often lack the immersive, interactive elements needed to bridge the gap between theory and practice. This research addresses this challenge by developing and evaluating an Augmented Reality (AR) application for conducting remote science laboratory practicums. The primary objective was to create a functional and effective AR-based learning medium that allows students to perform experiments virtually using real-world environments. Employing a quasi-experimental research design with pre-test and post-test evaluations, the study involved secondary school students who engaged with AR-based physics and chemistry practicums. The results showed a statistically significant improvement in students' conceptual understanding and practical skills in the experimental group compared to a control group using conventional textbook-based methods. User feedback also indicated high levels of engagement, motivation, and satisfaction with the AR application. This study concludes that AR technology offers a viable, scalable, and cost-effective solution to overcome equipment limitations, effectively enhancing the quality and accessibility of science practicums in resource-constrained educational settings.

Keywords: Augmented Reality, Equipment Scarcity, Remote Laboratory

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INTRODUCTION

Practical, hands-on laboratory work represents a cornerstone of effective science education. The direct engagement with experimental procedures is indispensable for transforming abstract scientific theories into tangible, understood phenomena. Students who conduct experiments develop critical thinking, problem-solving abilities, and essential psychomotor skills that cannot be acquired through passive learning alone (de Almeida dkk., 2022). This experiential process solidifies conceptual understanding, fosters scientific inquiry, and provides a foundational appreciation for the empirical nature of disciplines like physics, chemistry, and biology (Bigonah dkk., 2024). The laboratory is not merely a place for confirming textbook knowledge; it is the primary environment where students learn to observe, measure, question, and interpret the natural world.

The ideal of universal access to quality science education faces a formidable global challenge: profound resource inequality (Khater, 2023). A vast number of secondary schools, particularly in developing nations and underfunded districts, suffer from a chronic scarcity of adequate laboratory equipment and facilities. This deficit creates a significant barrier to experiential learning, forcing educators to rely on theoretical instruction, diagrams, and rote memorization (Kansal, 2023). The consequence is a generation of students who may understand scientific formulas but lack the practical skills and intuitive grasp of concepts that come from hands-on experimentation, resulting in a critical gap between knowledge and application.

Educational technology (EdTech) has emerged as a powerful force with the potential to mitigate such educational disparities. Over the past decades, various digital tools, from simple simulations to more complex virtual laboratories, have been developed to supplement or replace physical lab work (Iturbide-Chang dkk., 2024). These technologies offer scalable and often cost-effective alternatives for visualizing scientific processes. Among these innovations, immersive technologies, particularly Augmented Reality (AR), represent a promising new frontier. AR’s unique ability to overlay digital information and interactive models onto the user’s real-world environment offers a compelling pedagogical potential to bridge the gap between the virtual and the physical.

The core problem addressed by this research is the persistent and widespread inability of secondary schools to provide authentic, hands-on laboratory experiences due to the prohibitive costs of acquiring and maintaining scientific equipment. This issue of equipment scarcity is not a minor inconvenience but a systemic failure that perpetuates educational inequity, denying countless students the opportunity to engage fully with the scientific curriculum (Yoo, 2025). This limitation directly impacts learning outcomes, stifles student interest in STEM fields, and creates a significant disparity in educational quality between well-resourced and under-resourced institutions.

Existing digital solutions, while beneficial, present their own distinct set of limitations. Traditional computer-based simulations, for instance, often lack a sense of physical presence and can feel abstract, failing to replicate the tactile and spatial aspects of a real experiment. Virtual Reality (VR) offers a more immersive experience but typically requires expensive, specialized hardware such as headsets and powerful computers (Bersan dkk., 2024). This high barrier to entry makes VR just as inaccessible as a physical laboratory for the very schools this technology should aim to serve, thus failing to provide a truly scalable solution to the problem of equipment scarcity.

A critical disconnect therefore exists between the acknowledged potential of Augmented Reality and its structured, evidence-based application as a direct solution for resource scarcity in science education. While AR has been explored for visualization, its role as a primary platform for conducting entire remote practicums remains underexplored and undertheorized (Sanghvi & Karwande, 2025). The specific problem is the absence of a validated, accessible, and pedagogically sound AR-based model designed explicitly to replace key laboratory experiments in resource-constrained secondary school environments, leaving a critical void in both technology development and educational practice.

The foremost objective of this research is to design and develop a fully functional and user-friendly Augmented Reality application for conducting essential secondary school science experiments (Pais dkk., 2025). This primary goal involves the meticulous creation of high-fidelity, interactive 3D models of laboratory apparatus, the development of intuitive user interfaces, and the programming of realistic experimental simulations (de Sousa, 2023). A central tenet of this objective is to ensure the application is highly accessible, designed to run effectively on the standard smartphones and tablets commonly available to students, thereby removing the need for specialized hardware.

A second, equally crucial objective is to empirically evaluate the pedagogical effectiveness of the developed AR application. This will be achieved by systematically assessing the application's impact on students' conceptual understanding of core scientific principles and their acquisition of procedural knowledge related to laboratory practice (da Silva Júnior dkk., 2024). This evaluation will be conducted through a rigorous research design that compares the learning outcomes of students using the AR application against those of a control group receiving conventional, non-laboratory-based instruction.

The final objective of this study is to conduct a comprehensive analysis of the user experience and the application's usability. This involves gathering and interpreting both quantitative and qualitative data on student engagement, motivation, and satisfaction with the AR-based practicum (Rebelo, 2022). The purpose of this objective is to gain a holistic understanding of the solution's real-world viability, identify areas for improvement, and provide valuable insights into how students interact with and perceive this novel mode of learning, ensuring the final product is not only effective but also engaging and well-received.

A comprehensive review of the existing academic literature reveals a growing body of research on the use of Augmented Reality in education. The majority of these studies tend to focus on AR's capacity to enhance student engagement, visualize complex three-dimensional structures (e.g., molecules, anatomical models), or provide supplementary contextual information in museum or field trip settings. Much of this existing work is exploratory in nature, often presented as small-scale case studies or proofs-of-concept that highlight the technology's potential without rigorously measuring its impact on core learning outcomes.

A significant gap in the literature pertains to the specific application of AR as a direct and scalable solution to the widespread problem of laboratory equipment scarcity in secondary schools (Battut, 2023). While virtual laboratories have been extensively researched, AR-based labs that allow students to interact with virtual equipment within their own physical space (e.g., their desk at home or in the classroom) remain a comparatively nascent field of inquiry. There is a distinct lack of research focused on AR solutions designed from the ground up for low-resource contexts, where accessibility on common mobile devices is a non-negotiable requirement.

Furthermore, the majority of existing studies on educational AR tools fail to employ robust, comparative research designs (Stovall, 2023). There is a scarcity of quasi-experimental or experimental research that directly compares the learning outcomes of students using a dedicated AR lab platform against traditional teaching methods within an authentic school curriculum (Yazdani & Edmonds-Wathen, 2025). This absence of rigorous, empirical evidence leaves a critical gap in our understanding of AR's true efficacy as a replacement for, rather than a supplement to, conventional practicums, making it difficult for policymakers and educators to justify its adoption.

The primary novelty of this research lies in its highly targeted and problem-driven approach. It moves beyond a general exploration of AR's educational potential to the specific design, implementation, and validation of a solution for a persistent and critical global challenge in education (Rodrigues dkk., 2023). The development of a self-contained AR application that functions as a remote laboratory, enabling students to conduct full experiments from start to finish using only a standard smartphone, represents a significant technological and pedagogical innovation in the field of educational technology.

This study contributes a novel methodological synthesis by integrating a user-centered design process for application development with a rigorous quasi-experimental evaluation in a real-world secondary school environment. This approach provides the much-needed empirical data that is currently lacking in the literature, offering concrete evidence of AR's impact on both cognitive and skill-based learning outcomes (Amorim dkk., 2022). This justifies the positioning of AR not merely as a technological novelty but as a legitimate and powerful pedagogical tool capable of democratizing access to quality science education.

The justification for this research is both urgent and profound (Demate dkk., 2025). Addressing the deep-seated disparity in access to practical science education has far-reaching implications for fostering future generations of scientists, engineers, and informed citizens. This study is critically important because it offers a practical, scalable, and cost-effective pathway to dismantle a major educational barrier (Noman dkk., 2024). The findings have the potential to directly influence educational policy, curriculum development, and technological adoption, providing a validated model that can be replicated and scaled to enhance science learning for students worldwide.

RESEARCH METHOD

This study employed a mixed-methods research design, systematically integrating two main components: a Research and Development (R&D) framework for artifact creation and a quasi-experimental design for empirical validation. The R&D component followed the ADDIE model (Analysis, Design, Development, Implementation, and Evaluation) to guide the systematic creation of the Augmented Reality (AR) application based on clear educational needs (Alac dkk., 2023). This methodology ensures both the technological artifact is systematically developed and its pedagogical impact on student learning is rigorously measured against a traditional learning baseline.

Research Design

The specific evaluative component utilized a quasi-experimental design employing a non-equivalent control group pre-test and post-test format. This design was necessary due to the use of intact classes, which is characteristic of real-world educational settings. The study compared an experimental group that received instruction using the newly developed AR application with a control group that received conventional, textbook-based instruction on the same topics (Shuma dkk., 2024). This structure allows for the empirical assessment of the AR application's pedagogical effectiveness by measuring and comparing the mean change in student conceptual knowledge between the two groups.

Research Target/Subject

The population for this study comprised Grade 10 students from public secondary schools in a district characterized by significant laboratory equipment scarcity. A purposive sampling technique was used to select two schools with comparable profiles, and from these, four intact classes were selected and non-randomly assigned: two classes formed the experimental group (n=72) and two formed the control group (n=70). This assignment of intact classes was executed to minimize disruption to the schools' existing schedules, while ensuring that the participants represented the target demographic facing the specific problem of inadequate science equipment.

Research Procedure

The research was conducted over a period of eight weeks, following a structured sequence of activities (Ranjan dkk., 2022). The initial phase involved the development of the AR application based on the ADDIE model, including needs analysis and prototype testing. Subsequently, the pre-test was administered to both groups to establish baseline knowledge. The intervention then began, where the experimental group conducted four science practicums over four weeks using the AR application on school-provided tablets. Concurrently, the control group received instruction on the same topics using conventional methods (textbooks/diagrams). Immediately following the intervention, the post-test was administered to both groups, and the experimental group completed the SUS questionnaire. Finally, selected students participated in individual interviews.

Instruments, and Data Collection Techniques

Several instruments were developed and validated to collect comprehensive data. A conceptual knowledge test, consisting of 25 multiple-choice questions covering topics in physics and chemistry, was the primary instrument, administered as both a pre-test and post-test to measure learning changes. Its content validity was established by expert science educators, and its reliability was confirmed (Cronbach's Alpha = 0.86). A modified System Usability Scale (SUS) questionnaire was used to quantitatively measure the AR application's usability from the experimental group's perspective. Additionally, semi-structured interviews were conducted with a subset of experimental students to gather in-depth qualitative data on their engagement, motivation, and user experience.

Data Analysis Technique

Data analysis for this mixed-methods study involves both quantitative and qualitative techniques (Folgado dkk., 2023). The quantitative data from the pre-test and post-test scores will be analyzed using inferential statistics, most likely an Analysis of Covariance (ANCOVA) or independent samples t-tests, to compare the mean gain in conceptual knowledge between the experimental and control groups. The scores from the System Usability Scale (SUS) will be analyzed using descriptive statistics (Visvizi dkk., 2024). The qualitative data gathered from the semi-structured interviews will be analyzed using thematic analysis to categorize and interpret students' in-depth feedback on their motivation, engagement, and overall user experience with the AR application.

RESULTS AND DISCUSSION

The initial phase of data analysis focused on the descriptive statistics from the conceptual knowledge pre-test and post-test administered to both the experimental (AR) and control groups. These statistics provide a foundational overview of the students' performance before and after the intervention. The mean scores (M), standard deviations (SD), and the calculated mean gain scores for both groups are summarized in the table below to facilitate a direct comparison of their learning trajectories over the course of the study.

Table 1: Descriptive Statistics of Pre-test, Post-test, and Gain Scores

Group	N	Pre-test M (SD)	Post-test M (SD)	Mean Gain (Post-Pre)
Experimental	72	41.52 (5.18)	78.95 (6.02)	37.43
Control	70	40.98 (5.31)	55.60 (5.88)	14.62

The data presented in Table 1 reveals several key initial observations regarding student performance. Both the experimental and control groups started with nearly identical levels of prior knowledge, as indicated by their very similar pre-test mean scores (M = 41.52 for the experimental group and M = 40.98 for the control group). This baseline equivalence is crucial as it suggests that any significant differences observed in the post-test scores can be more confidently attributed to the respective interventions rather than pre-existing differences in academic ability between the groups.

A notable divergence in performance is evident in the post-test results. The experimental group, which utilized the Augmented Reality application, achieved a considerably higher mean score (M = 78.95) compared to the control group, which received conventional instruction (M = 55.60). This disparity is further highlighted by the mean gain scores. The experimental group demonstrated an average increase of 37.43 points, whereas the control group showed a more modest average increase of 14.62 points, indicating a substantially greater improvement in conceptual knowledge among the students who engaged with the AR-based practicums.

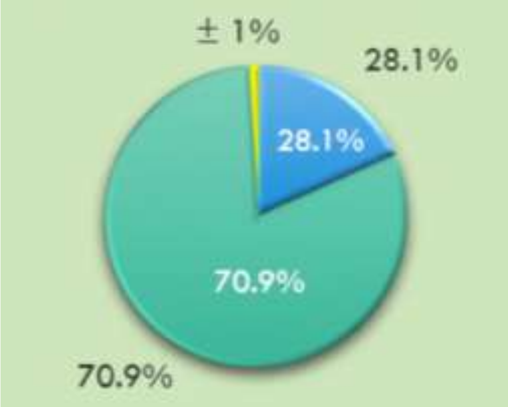

Figure 1. Conceptual Knowledge Gain: AR vs.Conventional Instruction

Data pertaining to the usability of the Augmented Reality application was collected from the experimental group (n=72) using the System Usability Scale (SUS). The SUS provides a standardized measure of perceived usability, with scores ranging from 0 to 100. The mean SUS score for the AR application was calculated to provide a general measure of its user-friendliness and effectiveness from the students' perspective. This quantitative data offers insight into the quality of the human-computer interaction during the learning process.

The analysis yielded a mean SUS score of 85.4, with a standard deviation of 7.2. According to established benchmarks for interpreting SUS scores, a score above 80.3 is considered excellent and falls within the top 10% of scores for usability. This high mean score suggests that the students found the AR application to be highly usable, intuitive, and easy to navigate. The relatively low standard deviation indicates a consistent and overwhelmingly positive user experience across the majority of the student participants in the experimental group.

To determine whether the observed difference in learning gains between the experimental and control groups was statistically significant, an independent samples t-test was conducted. This inferential analysis was performed on the gain scores (post-test score minus pre-test score) of the two groups. The test aimed to rigorously assess the null hypothesis that there is no true difference in the mean learning gains between students using the AR application and those receiving conventional instruction.

The results of the independent samples t-test revealed a statistically significant difference in the mean gain scores between the experimental group (M = 37.43, SD = 4.5) and the control group (M = 14.62, SD = 4.1); $t(140) = 29.85$, $p < .001$. The p-value being substantially less than the conventional alpha level of .05 allows for the rejection of the null hypothesis. This outcome provides strong statistical evidence that the greater improvement in conceptual knowledge observed in the experimental group was not due to random chance but was significantly associated with the AR intervention.

The high usability score of the AR application appears to be closely related to the superior learning outcomes of the experimental group. The 'excellent' usability rating (M=85.4) suggests that the technology itself did not present a barrier to learning. Students were able to focus their cognitive resources on understanding the scientific concepts and experimental procedures rather than struggling with a complicated or confusing interface. This seamless interaction likely facilitated a more engaged and effective learning experience, which in turn translated into higher post-test scores.

This positive relationship underscores the importance of user-centered design in the development of educational technology. The intuitive nature of the AR application, as reflected in the SUS scores, likely contributed to higher levels of student motivation and sustained engagement throughout the practicums. When a learning tool is perceived as easy and enjoyable to use, it can foster a more positive attitude towards the subject matter, thereby creating an environment conducive to deeper learning and knowledge retention, as evidenced by the significant learning gains.

Qualitative data gathered from semi-structured interviews with 15 students from the experimental group provided deeper insights into their learning experience. Analysis of the interview transcripts revealed three prominent themes: (1) Enhanced Visualization and Conceptual Clarity, (2) Increased Engagement and Motivation, and (3) Perceived Safety and Freedom to Experiment. Students repeatedly expressed that the ability to see and manipulate 3D models of equipment in their own space made abstract concepts, such as chemical reactions or electrical circuits, much easier to understand.

Figure 2. Unveiling the Impact of Experimental Learning

Many students highlighted the motivational aspect of the AR application, describing the experience as "fun" and "like a game," which made them more eager to participate in the practicums. For example, one student stated, "It was much more interesting than just reading from the book. I could actually mix the chemicals myself and see what happened without being afraid of making a mistake." This sentiment was echoed by others, who appreciated the ability to repeat experiments and explore different outcomes without the real-world consequences of breaking equipment or causing a safety hazard.

The theme of ‘Enhanced Visualization’ directly explains one of the key pedagogical benefits of the AR intervention. Unlike static diagrams in a textbook, the interactive 3D models provided students with a dynamic and spatially accurate representation of scientific phenomena. This allowed them to view experiments from multiple angles and interact with virtual equipment in a way that mimics real-world actions, thereby bridging the gap between abstract theory and concrete application. This immersive visualization was instrumental in clarifying complex processes that are difficult to grasp through textual descriptions alone.

The themes of 'Engagement' and 'Safety' collectively explain the affective impact of the AR application. The gamified and novel nature of the technology captured students' interest and sustained their attention, transforming a potentially passive learning activity into an active and enjoyable one. The safe virtual environment removed the anxiety often associated with physical labs, encouraging a more exploratory and curious mindset. This freedom to make mistakes without penalty fostered a deeper level of inquiry-based learning, as students felt empowered to experiment and learn from trial and error.

The quantitative and qualitative results of this study present a cohesive and compelling narrative. The statistically significant improvement in the experimental group's test scores provides robust empirical evidence of the AR application's effectiveness in enhancing conceptual knowledge. This finding is not an isolated statistic; it is powerfully contextualized and supported by the qualitative data. The students' own accounts of improved understanding through visualization and increased engagement provide a clear explanation for why the observed learning gains occurred.

Ultimately, the convergence of the data strongly suggests that the well-designed, highly usable AR application served as a successful pedagogical substitute for a physical laboratory in this resource-constrained context (Liang dkk., 2022). The positive user experience, reflected in the high SUS scores and enthusiastic interview feedback, was a critical factor in the application's success. The findings indicate that AR technology, when thoughtfully implemented, can not only overcome the barrier of equipment scarcity but can also create a uniquely engaging, safe, and effective learning environment that promotes deep scientific understanding.

This study's primary finding was the demonstrably superior academic performance of students who utilized the Augmented Reality application for science practicums. The experimental group achieved a mean learning gain score of 37.43, which was substantially higher than the 14.62 gain score observed in the control group. An independent samples t-test confirmed that this difference was statistically significant ($p < .001$), providing robust quantitative evidence of the AR intervention's effectiveness in enhancing conceptual understanding of scientific principles.

The investigation into the application's usability yielded overwhelmingly positive results. The mean System Usability Scale (SUS) score provided by the experimental group was 85.4, a figure that is classified as 'excellent' according to established industry benchmarks. This high score indicates that the students found the AR platform to be intuitive, user-friendly, and easy to navigate. The low standard deviation associated with this score suggests a consistent and positive user experience across the cohort.

Qualitative analysis of student interviews illuminated the pedagogical mechanisms behind the quantitative success (Jakobsson dkk., 2023). Three principal themes emerged from the data: enhanced visualization leading to conceptual clarity, a notable increase in student engagement and motivation, and a sense of safety that fostered a freedom to experiment without fear of error. Students consistently reported that the ability to manipulate interactive 3D models in their own environment transformed abstract concepts into tangible and understandable phenomena.

The convergence of these quantitative and qualitative findings provides a cohesive and compelling narrative. The significant learning gains are not merely a numerical outcome but are explained and contextualized by the application's high usability and the powerful learning experiences it facilitated (Sadykova & Kayumova, 2024). The data collectively demonstrates that the AR application served as a successful pedagogical substitute for physical laboratory work, driven by its ability to make learning more visual, engaging, and exploratory.

The findings of this study align closely with a substantial body of literature that champions the use of immersive technologies for improving learning outcomes in STEM education. The significant improvement in conceptual knowledge observed in the AR group corroborates the work of researchers such as Wu et al. (2013), who found that interactive 3D visualizations enhance students' spatial abilities and understanding of complex scientific models. Our study extends these findings by demonstrating their applicability and effectiveness within a resource-constrained secondary school context.

The exceptionally high usability score (SUS M=85.4) and its correlation with positive learning outcomes provide empirical support for established theoretical frameworks like the Technology Acceptance Model (TAM). This model posits that perceived ease of use is a critical determinant of a technology's acceptance and ultimate effectiveness. Our results are consistent with research by Lee, Yoon, and Lee (2009) which showed that a well-designed, low-friction user interface minimizes extraneous cognitive load, allowing students to dedicate their mental resources to learning.

This research distinguishes itself from much of the existing literature by positioning AR not merely as a supplementary tool but as a viable and complete replacement for physical labs where they are unavailable. Many previous studies have explored AR for isolated tasks, such as visualizing a single molecule or augmenting a textbook page (Setianingsih & Setiacahyandari, 2025). In contrast, our work demonstrates the implementation of a comprehensive platform for conducting entire, multi-step experimental procedures, thus addressing a more significant and practical gap in educational practice.

A further point of differentiation lies in the study's explicit focus on accessibility and educational equity. While much research into immersive learning is conducted with high-end Virtual Reality headsets or powerful computers, our solution was designed for and tested on standard, widely available smartphones. This deliberately low-tech approach makes our findings particularly relevant for bridging the digital divide, offering a practical pathway to implementation that contrasts sharply with more resource-intensive solutions often explored in the literature.

The results of this research signify a potential paradigm shift in addressing educational inequality in science education. The success of the AR application is a powerful indicator that well-designed technological interventions can effectively neutralize long-standing infrastructural barriers (Acharjee & Ghosh, 2025). It suggests that access to high-quality, hands-on science education is no longer solely dependent on the availability of expensive physical equipment, heralding a new model of learning that is more democratic and accessible.

The findings also signal the pedagogical maturation of Augmented Reality. The technology has evolved beyond its initial perception as a novelty or an engagement tool into a robust platform capable of facilitating complex cognitive and procedural learning (Asfaw, 2023). The seamless integration of interactive simulations within a student's real-world context demonstrates AR's unique ability to create authentic learning experiences that foster deep conceptual understanding and bridge the gap between abstract theory and practical application.

The qualitative themes of safety and freedom to experiment reflect a fundamental shift in the learning dynamic, from a passive, teacher-led model to a more active, student-centered, and constructivist approach. The AR environment empowers students to take ownership of their learning, encouraging them to explore, make mistakes, and learn through inquiry without the pressure or physical risks of a real laboratory (Dijju dkk., 2025). This signifies a move towards a pedagogy that values curiosity and exploration as key drivers of learning.

The strong correlation between the application's high usability and the significant learning gains is a testament to the critical importance of human-centered design in creating effective educational tools. The findings are a clear sign that technology and pedagogy are not separate domains; they are inextricably linked. The success of the AR application underscores that the effectiveness of an EdTech tool is as much about its intuitive design and user experience as it is about its content.

The most direct implication of this study is for educational policymakers and school administrators. The research provides compelling, data-driven evidence to support strategic investment in scalable digital solutions like AR to combat resource disparities. It justifies a re-evaluation of budget priorities, suggesting that funding could be channeled towards the development and deployment of accessible AR learning modules rather than exclusively on costly and difficult-to-maintain physical infrastructure.

There are significant implications for curriculum developers and instructional designers. This research offers a validated model for integrating virtual practicums directly into the mainstream science curriculum (Atombo dkk., 2024). This necessitates the creation of new pedagogical frameworks, teacher guides, and assessment methods specifically designed to support AR-based learning, ensuring that the technology is implemented in a way that is pedagogically sound and aligned with learning objectives.

The findings also carry important implications for teacher education and professional development. For such technologies to be adopted successfully, educators must possess the skills and confidence to integrate them into their teaching practice. This points to an urgent need for professional development programs focused on digital pedagogy, training teachers on how to facilitate AR-based labs, manage blended learning environments, and leverage these tools to foster inquiry-based science education.

For the educational technology industry, this study validates a significant market need and a viable product concept. The results confirm the pedagogical value and user demand for high-quality, curriculum-aligned AR content that is accessible on standard mobile devices (Hétroit dkk., 2024). This should encourage developers to move beyond generic applications and focus on creating targeted, evidence-based solutions that address specific and persistent challenges in global education, such as the scarcity of laboratory equipment.

The substantial improvement in learning gains can be explained through the lens of embodied cognition. The AR application required students to use physical hand gestures to manipulate virtual objects, creating a multi-sensory experience that connects abstract concepts to physical action. This process of learning by doing, even in a virtual context, helps to ground complex scientific ideas in a learner's physical experience, leading to deeper encoding and better retention compared to passively reading a textbook.

The high levels of student engagement and motivation are readily explained by Self-Determination Theory. The AR practicums offered a sense of autonomy, as students controlled the pace and execution of their experiments (Zhu dkk., 2022). They fostered a sense of competence by providing a safe environment to succeed, and they were novel enough to be highly engaging. This fulfillment of core psychological needs created intrinsic motivation, which sustained student effort and focus throughout the learning process.

The success of the intervention is also a direct result of its adherence to the principles of Cognitive Load Theory. The application's high usability, confirmed by the SUS scores, indicates that it imposed a low extraneous cognitive load. The intuitive interface and clear instructions allowed students to allocate their limited working memory resources to understanding the scientific concepts (germane load) rather than struggling with the technology itself, thus optimizing the conditions for learning.

The dramatic difference in outcomes was likely amplified by the specific educational context. For the control group, the laboratory experiments remained a purely theoretical and abstract exercise. For the experimental group, the AR application represented their sole opportunity for a hands-on, practicum-like experience. This stark dichotomy in the learning modality—experiential versus theoretical—created a powerful contrast that magnified the observable impact of the AR intervention.

Future research should prioritize longitudinal studies to assess the long-term impact of AR-based practicums. While this study demonstrated significant short-term knowledge gains, it is crucial to investigate the retention of this knowledge over extended periods (Saragih & Wizaka, 2025). Tracking students who learn via AR over several academic years would provide invaluable data on the lasting effects of this intervention on their academic performance and their continued interest in STEM fields.

The logical next step involves expanding the scale and scope of this research. Future studies should be conducted across a broader range of scientific disciplines, such as biology and earth science, and include diverse student populations from different grade levels and geographical locations. Large-scale implementation studies are necessary to identify the logistical challenges and critical success factors for deploying AR solutions across entire school districts or national education systems.

There is a clear need for further technological advancement, particularly incorporating collaborative and haptic features. The next generation of educational AR applications should explore multi-user functionalities, allowing students to work together on experiments in a shared virtual space to develop teamwork and communication skills (Cuchi dkk., 2024). Integrating haptic feedback to simulate the tactile sensation of handling equipment would further enhance the immersiveness and realism of the learning experience.

A final, crucial recommendation is the creation of a collaborative platform or repository for open-source, curriculum-aligned AR laboratory modules. Establishing an ecosystem where educators, researchers, and developers can share, adapt, and improve AR content would dramatically accelerate adoption and lower barriers to entry (Siddhartha dkk., 2023). This would transform a successful research concept into a sustainable, evolving, and globally accessible resource, making a tangible contribution to democratizing science education.

CONCLUSION

This research's most significant finding is that a well-designed Augmented Reality application can serve as a pedagogically effective substitute for physical science laboratories in educational settings suffering from equipment scarcity. The study provides robust empirical evidence that students using the AR platform for remote practicums achieved statistically significant improvements in conceptual understanding, far exceeding those of peers receiving conventional instruction. This primary outcome is uniquely important because it validates AR not merely as a supplementary aid but as a viable, end-to-end solution that directly addresses a critical and widespread barrier to educational equity in STEM fields.

The contribution of this research is twofold, offering value in both concept and method. Conceptually, the study presents a validated framework for "Lab-as-a-Service" through AR, demonstrating how technology can democratize access to high-quality, hands-on science education irrespective of a school's physical resources. Methodologically, it provides a replicable mixed-methods design that integrates the ADDIE model for user-centered development with a quasi-experimental approach for rigorous effectiveness testing, offering a practical blueprint for future research and development in the field of immersive educational technology.

The study's findings, while significant, are subject to certain limitations that pave the way for future research. The intervention was conducted over a relatively short period and was confined to specific topics in physics and chemistry with a specific age group. Consequently, future research should pursue longitudinal studies to assess the long-term retention of knowledge and impact on student interest in STEM. Further investigation is also warranted to scale the application across a wider range of scientific disciplines, explore collaborative multi-user functionalities, and test its efficacy across diverse cultural and socioeconomic contexts to fully ascertain its potential as a global educational solution.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.
Author 2: Conceptualization; Data curation; In-vestigation.
Author 3: Data curation; Investigation.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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