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Integrating Augmented Reality and Deep Learning in an Interactive STEAM-Based Digital Storybook to Enhance Elementary School Students' Science Literacy

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ABSTRACT

Science literacy among primary school students remains a significant challenge in equipping future generations to meet the demands of the 21st century. Prior meta-analyses demonstrated that Augmented Reality (AR) markedly enhances learning outcomes and student engagement, but the STEAM method yields a moderate effect on science achievement. Nonetheless, the amalgamation of AR, STEAM, and deep learning for individualised learning in scientific education remains little examined. This study aims to develop and evaluate an Interactive Digital Storybook that utilises AR and deep learning to enhance science literacy in primary schools. The research utilised the Successive Approximation Model (SAM), which prioritises iterative design, prototyping, and refinement. The development process had three steps: (1) preparation, which included needs analysis through interviews, observations, and document studies in three East Java elementary schools; (2) iterative design and development, which included storyboarding, interface design, AR feature creation, deep learning integration, and prototype testing; and (3) implementation, which included one-on-one and small group evaluations with teachers and students. Data were gathered via expert validation (content, pedagogy, technology) and user feedback. The data were gathered through expert validation in content, pedagogy, and technology, as well as a small trial with 45 children from three public elementary schools in East Java, Indonesia. The validation results showed that the project was very likely to work (Content = 92%, Pedagogy = 90%, technology = 94%). Students reported that interactive stories, AR-based 3D simulations, and gamified challenges increased their interest and motivation. These data indicate that the produced media is suitable for additional effectiveness testing in the second year.

Keywords: Augmented Reality, Deep Learning, Interactive Digital Storybook, STEAM

INTRODUCTION

The Golden Generation of Indonesia 2045 is expected to have excellent literacy skills in science, finance, technology, and culture, which are all necessary for a developed, fair, and prosperous country (Amran et al., 2020; Irfani et al., 2021; Pangarso et al., 2020). Scientific literacy is one of the most important skills since it is necessary to deal with the problems of the 21st century (Malihah, 2015; Rosidah & Cahyaningtyas, 2024; Samala et al., 2024). The Programme for International Student Assessment (PISA) states that scientific literacy encompasses not only the ability to conduct experiments but also the capacity to describe scientific phenomena, design and evaluate research, and interpret results scientifically (Höttecke & Allchin, 2020). Students need to have a solid understanding of concepts, be able to think critically, and apply their scientific knowledge to their daily lives.

Unfortunately, multiple studies have shown that the scientific literacy levels of Indonesian students remain low. PISA results and local studies indicate that evaluating and designing scientific investigations are the weakest areas, requiring extra attention (Höttecke & Allchin, 2020). This syndrome has significant consequences: students struggle with learning, lack critical thinking skills, and experience difficulty adjusting to the modern environment. Also, students who do not know much about science are more likely to believe false information, make bad decisions, and not be able to do their jobs well (Kelly & Licona, 2018; Sharon & Baram-Tsabari, 2020). To make a thoughtful, critical, and future-ready generation, we need to improve scientific literacy quickly.

To solve this problem, different ways of learning have been devised. The Science, Technology, Engineering, Arts, and Mathematics (STEAM) approach has been shown to enhance students' engagement and comprehension of science more innovatively and practically (Afkar et al., 2024; Rohmania, 2024; Tillah, Nurmazia Firahma; Subekti, 2025). Project-based and exploratory STEAM can promote active student participation; however, much research focuses solely on integrating scientific disciplines without enhancing the efficacy of interactive digital technologies. Conversely, technology-driven educational tools, such as Augmented Reality (AR), have demonstrated beneficial effects on learning outcomes and student engagement (Czok et al., 2023; Kumar & Gorai, 2025; Lin & Yu, 2023). AR provides learning experiences through 3D simulations, interactive animations, and visual settings that help students grasp scientific concepts realistically and engagingly (Abinaya & Vadivu, 2023; AlGerafi et al., 2023; Ugli et al., 2025). Nonetheless, the majority of research continues to employ AR in a static context, rather than integrating it with holistic pedagogical frameworks, such as STEAM.

Recent research indicate that personalized learning is crucial for enhancing scientific literacy, particularly in basic education. Deep learning technology can look at how students learn, change the complexity of the content, and provide each student personalized suggestions based on their requirements and learning (Naseer et al., 2024; Shaik et al., 2025; Smirani & Yamani, 2024). The application of deep learning in interactive storytelling and AR educational media is infrequently examined, especially concerning scientific literacy in primary education.

As a result, there is still a lack of study on how to combine STEAM methods, AR technologies, and deep learning-based artificial intelligence into a single, dynamic, and customizable learning environment. Bringing these three things together will make learning more personalized, interesting, and useful, and it will also help students become more scientifically literate in both their minds and hearts. The goal of this study is to make a STEAM-based Interactive Digital Storybook that uses AR and a deep learning method to improve elementary school kids' scientific literacy. This study explicitly investigates the product validation phase to evaluate the feasibility of the content, pedagogy, and technology employed in the produced media.

RESEARCH METHOD

Research Design

This work seeks to develop an AR-enhanced Interactive Digital Storybook for STEAM, employing a Deep Learning approach to improve the scientific literacy of primary school children. The item that was manufactured contains these things: STEAM-based to help students understand across disciplines, using AR to make 3D visuals interactive, using deep learning to tailor learning to each student, using interactive digital narratives, making virtual experiments easier, improving scientific literacy through AR-based reflection and challenges, adding gamification features to boost motivation, and using learning analytics to track student progress. The method used is Design and Development Research (DDR), which is based on the Successive Approximation Model (SAM). DDR is more flexible than ADDIE because it puts a higher priority on quick iteration, continuing validation, and ongoing improvement.t (Allen, 2012).

Research Procedure

This research employed the Successive Approximation Model (SAM), which consists of three primary phases: preparation, iterative design, and iterative development. Each step was done with care to make sure that the end product was both useful for teaching and possible with technology, satisfying the needs of both the students and the curriculum.

Preparation Phase

The study began with an evaluation of requirements to identify the essential components needed for development. This strategy comprised figuring out what scientific literacy pupils needed, making sure that these needs fit with what they were learning in school, checking if schools were ready for technology, and thinking about how students' cognitive qualities might affect how they used media. Following that, a thorough review of the literature on digital media, AR, deep learning, and the use of the STEAM approach in elementary science education was undertaken to collect data. This step set the stage for the design stage in both thoughts and practical problems.

Iterative Design Phase

Prototyping was the first step in the iterative design phase. This included making the storyboard, user interface, interactive storyline, AR features, and a simple deep learning algorithm to give users personalized material. Then, experts in the subject, education, and technology checked the design with standardized evaluation techniques to make sure it was right. After validation, alpha testing was done on a small scale to see how well the features performed, how easy they were to use, and how to make them better before going on to the next level.

Iterative Development Phase

The iterative development phase began with refinement, which involved making changes to the application based on feedback from people during alpha testing. Then came beta testing, which was conducted with a small sample of students (N = 45) to assess the usefulness of the content, the effectiveness of the teaching methods, and the stability of the technology. The outcomes of this stage were crucial for the finalisation step, during which the application was refined and improved to an excellent standard. This ensured that the final product was ready for testing its effectiveness and for use in more classrooms.

Population and Sample

To ensure the representativeness of the study context, the population and sample were meticulously delineated according to precise criteria. The group consisted of fourth- to sixth-grade elementary school students in East Java who had access to digital devices (such as tablets or smartphones) and internet connectivity. We chose this age group because children of this age typically have good reading skills, can reason logically, and are ready to explore interactive digital content.

The sample was chosen via purposive sampling based on three main factors: the schools possessed information and communication technology (ICT) facilities, the teachers were willing to try new ways of teaching, and the students had access to digital devices. Three schools were chosen as research sites based on these criteria: YIMI Gresik Elementary School, Zainuddin Sidoarjo Elementary School, and Kaliasin Surabaya Elementary School. There were 45 students in the small trial, with 15 students coming from each of the chosen schools.

Research Instruments

This study employed both quantitative and qualitative metrics to comprehensively evaluate the effectiveness and feasibility of the developed application. The expert validation tools included three types of evaluation sheets: content validation, which looked at how well the material fit with curriculum standards, scientific literacy, and the STEAM approach; pedagogical validation, which looked at how well the teaching methods worked and how likely they were to get students interested; and technological validation, which looked at how easy it was to use, how well the AR features worked, and how well the deep learning components worked.

The student trial instruments included a questionnaire to measure students' interest, motivation, and thoughts about the application, and structured observation sheets to note how students used the application in class. The teacher interview tool also had a semi-structured interview guide that asked teachers what they felt about the app's usability, how well it fit into their classroom practice, and how it could help students become more scientifically literate. Before being utilized in the study, specialists validated all of the instruments for content validity to make sure they were correct, reliable, and suitable for the research goals.

Data Analysis

The data analysis in this study was conducted in several stages to ensure a comprehensive evaluation of the developed application. First, validity and feasibility analysis were performed using expert validation scores. The results were then categorised into four levels, as shown in Table 1. The feasibility percentage was calculated with the formula:

$$\text{Feasibility} = \frac{Obtained\ Score}{Maximum\ Score}\ x\ 100\%$$

Table 1. Category Criteria

Category	Criteria

Very Feasible	>85%
Feasible	70%–85%
Moderately feasible	50%–69%
Not feasible	<50%

The student trial analysis was conducted next. Descriptive analysis of questionnaire data on engagement, motivation, and perception was conducted using means and percentages. The scientific literacy test results were analysed using gain scores to assess the enhancement of students' comprehension following the session. Additionally, qualitative analysis of observational data was conducted to elucidate patterns of student interaction with the program in classroom settings. The analysis of teacher perceptions was conducted last. Thematic analysis was employed to examine data from semi-structured interviews, identifying common themes in teachers' viewpoints, the challenges they encountered when integrating media into practice, and suggestions for enhancing the effectiveness of media in the classroom.

RESULTS AND ANALYSIS

Need Analysis Phase

The needs analysis phase was conducted to identify the challenges associated with low science literacy among primary school students and to establish the preliminary requirements for developing the learning medium. We collected our data through interviews, observations, and document reviews at three elementary schools in East Java: YIMI Gresik Elementary School, Zainuddin Sidoarjo Elementary School, and Kaliasin Surabaya Elementary School. The results showed that teacher-centred lectures and textbook-based instruction are still the main ways that students learn science. Laboratory activities are still limited because there are not enough facilities, and technology-based learning resources are not used very often. As a result, students struggle to connect scientific concepts to their everyday lives, critically evaluate scientific research, and fully comprehend data and scientific evidence. Teachers emphasised the importance of interactive media that can transform abstract ideas into more concrete ones, utilise storytelling suitable for elementary students, provide students with both guided and independent learning opportunities, and allow them to conduct safe and engaging virtual experiments.

Literature evaluations further validated that the integration of STEAM methodologies, AR technology, and adaptive deep learning systems can substantially enhance students' motivation and comprehension. Meta-analysis studies demonstrate that AR has a significant influence on learning outcomes ($g = 0.919$) and STEAM has a medium effect ($ES = 0.71$). Combining the two could have a significant effect on education. It was also noted that the schools already had sufficient ICT infrastructure, including computers, projectors, and tablets, and that they were all connected to the internet; however, the quality varied from school to school. Students were already used to utilising digital gadgets, primarily for fun, but they did not have much experience using them for official study.

Design and Development of the Interactive Digital Storybook

Based on the identified demands, an interactive digital storybook was created by combining narrative text, coloured pictures, 3D AR animations, and STEAM-based activities personalised using a deep learning system. The storybook is about the experiences of Raka and Lila, two main characters who go through a "Dimensional Gate" to different themed worlds, like a realm of futuristic technology full of robots and smart devices. The book cover shows Raka and Lila in front of the luminous Dimensional Gate, with a technological world full of robots and holograms in the backdrop. This is intended to spark students' curiosity (see Figure 1). When students scan the cover, an AR feature allows them to view an animated introduction.

Figure 1. Cover Interactive Digital Storybook

Each thematic world contains STEAM information that is useful for improving kids' science literacy. During the requirement analysis phase, we looked at people's preferences for how things looked, how they used language, and how interactive they wanted things to be. The students may read the storybook on their phone or tablet. Each page has scannable AR icons that start 3D animations, virtual experiments, or interactive quizzes. The layout was made so that it could be read on a screen or in print in A5 size (14.8 cm × 21 cm). Students liked this size since it was easy to read and navigate. Each page has story parts, supporting pictures, AR/QR icons that let the students access digital content, and STEAM indicators that show that there are science, technology, engineering, arts, or math elements. The colour scheme uses gentle yet bright tones to keep students engaged without making them feel tired of looking at them. Each themed area has its own unique palette, such as neon blue for technology and natural green for the environment. To make sure it could be read on both digital and printed media, a child-friendly sans-serif font was employed (see Figure 2).

Figure 2. Colour and Text in the Interactive Digital Storybook

Illustrations of characters were developed to align with students' needs, portraying cheerful expressions, casual clothing, and active gestures in environments that are detailed yet simple to maintain focus on the storyline (see Figure 3).

Figure 3. Illustration and Characters

AR Activities, Personalisation, and Gamification Features

Each thematic world within the storybook contains AR-based simulations, 3D models, and animations that can be accessed by scanning embedded codes. For instance, in the tech industry, students can observe robots in motion and click on various parts of their bodies to discover their functions. The deep learning system makes learning even more personal by looking at how students engage with AR content and their quiz scores at the conclusion of each chapter. It then adjusts the level of difficulty or adds more challenges based on the student's performance. Points, medals, and leaderboards were added to make the tale more fun and motivate students to explore the material actively.

Content Validation and Practicality Evaluation

Experts checked the storybook for its content, teaching methods, and technology. The results showed that the validity was quite good, with scores of 92% for content, 90% for pedagogy, and 94% for technology. There were two levels of practicality testing. The one-on-one evaluation involved one teacher and three students, each with a different learning speed (rapid, medium, and slow). The results showed that both the kids and the teacher could utilise the storybook without any problems. However, some elements in the illustrations may be improved. The small group review included 45 students and three teachers. It showed that the kids were actively engrossed in the story, scanned AR codes, and finished STEAM challenges. Teachers noticed that students were genuinely interested in science issues and were quite engaged in interactive quizzes, where they actively discussed solutions.

In general, the results show that the interactive digital storybook does a good job of making science learning more fun, relevant, and participatory. AR elements helped turn abstract ideas into more concrete and real-world learning experiences. The deep learning system, on the other hand, allowed for adaptable learning paths that were personalised to each student's strengths and weaknesses. Additionally, the incorporation of gamification components maintained student interest and engagement over time. Notably, there were no major technical problems during the classroom deployment, which means that the product can be used in elementary science classes.

DISCUSSION

The findings of this study indicate that the developed interactive digital storybook is an effective method for improving science literacy among primary school pupils through the integration of STEAM, AR, deep learning, and gamification. The results are consistent with past studies showing that creative, tech-enhanced media can help students connect abstract scientific ideas to things they see and do in the real world (Firsova et al., 2024; Ghanbaripour et al., 2024; Sacristán et al., 2024). AR helps students see and interact with abstract ideas in a way that makes learning via doing easier (Anila et al., 2024; Gundala et al., 2022; Kononov et al., 2025; Velarde-Camaqui et al., 2025). The AR elements in the storybook gave students real-life examples of scientific ideas, which solved the shortcomings with traditional textbook- and lecture-based methods that were found during the requirements analysis.

The customization options in deep learning also match with the growing trend toward adaptable learning in educational systems. AI-driven adaptive systems can change the way students learn to fit their needs, which can make learning more effective and interesting (Khan & Sultan, 2025; Tariq, 2025; Waladi et al., 2025). The technology created in this study could change the level of difficulty and give pupils customized feedback based on how they used it. This study adheres to the tenets of diversified education, highlighting the significance of adaptive systems in addressing the varied needs of students in various classrooms (Tomlinson, 2017).

The addition of STEAM to the digital storybook also encouraged youngsters to explore different subjects, allowing them to learn about science, technology, engineering, the arts, and arithmetic. STEAM-based methods help people be creative, think critically, and solve problems, which are all important talents for the 21st century (Asrifan et al., 2025; Ramesh, 2025). The storybook's narrative-based design is in line with studies that shows how digital storytelling can boost student motivation and help them remember things by putting knowledge in relevant and familiar contexts (Bai et al., 2023; Wu et al., 2025).

The storybook's gamification elements, such as points, badges, and leaderboards, were also shown to greatly boost students' interest and motivation. This supports the findings of Shtayyat and Gawanmeh (2025) and Upadhyaya and Garg (2019), Some argue that gamification enhances learning by fostering a sense of achievement and sustained engagement. In this study, students confronted difficulties and interacted with dynamic content, demonstrating how gamification may convert passive learning into active exploration.

The positive outcomes of the practicality testing further substantiate the feasibility of incorporating AR-based STEAM media into real classroom settings. Teachers said that students were more interested, involved, and willing to work together during group activities. This supports the sociocultural thesis that learning is more effective when people connect with one another and share experiences (August & Henderson, 2025; Säljö, 2022). The collaborative involvement noted during small group evaluations demonstrates that the digital storybook facilitates individual learning while also encouraging peer discussions and collective problem-solving.

Even though these results are promising, there are a few things that need to be looked into in future studies. First, the infrastructure in the participating schools was sufficient, but the variation in internet quality could make it more challenging to use in remote or under-resourced locations. Second, while the deep learning system effectively delivered adaptive pathways, ongoing improvement and testing with bigger and more diverse populations are essential to guarantee the robustness and equity of personalisation. Lastly, the long-term impact of AR-based storybooks on students' advancement in science literacy and their application of learning in real-world situations necessitates additional research.

In summary, this study contributes to the growing body of research on technology-enhanced learning by demonstrating that incorporating AR, STEAM, and adaptive learning systems within a digital storytelling framework can enhance science literacy in primary school. The integration of narrative engagement, interactive visualisation, adaptive personalisation, and gamified incentives effectively targets both cognitive and affective aspects of learning, providing a comprehensive framework for science education in the digital era.

CONCLUSION

This project developed and tested an interactive digital storybook that utilises STEAM, AR, and deep learning to enhance elementary school students' understanding of science. The study utilised the Successive Approximation Model (SAM), facilitating iterative cycles of design, execution, and refinement, culminating in a product that is pedagogically sound, technologically viable, and contextually pertinent. The results showed that the storybook is very legitimate in terms of content, pedagogy, and technology. It also showed that it is helpful in one-on-one and small group evaluations, where both students and teachers reported being very engaged, motivated, and understanding what they were reading.

This study is unique because it combines three important elements, STEAM, AR, and deep learning, into a framework for digital storytelling that is also made more engaging through gamification. Prior research has examined the advantages of STEAM education and AR in isolation; however, the present study illustrates how the integration of these components can foster a customised, interactive, and adaptive learning environment. This integration addresses both the cognitive domain, by promoting critical thinking and scientific reasoning, and the affective domain, by enhancing motivation and engagement through narrative and gamification.

This study has two important effects. First, the storybook that was created provides a paradigm for utilising cutting-edge technologies in elementary education to address the issue of inadequate science literacy. Teachers can utilise the storybook as both an additional resource and a key component of project-based and inquiry-based learning. Second, the study opens up new areas of research into AI-driven personalisation in learning media, especially in situations where there is significant variability among learners.

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