

Development of augmented reality media for ecological themes in early childhood science learning



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Background: It is important to teach science about the environment and how it affects living things (ecology), particularly floods and volcanic eruptions. But teachers do not have many media resources to help them teach these topics to students in early childhood (EC).

Aim: This study aims to explain the analysis, design, development, implementation and evaluation (ADDIE) of ecological themes-based augmented reality media (ETBARM), particularly floods and volcanic eruptions, in science learning among EC students.

Setting: The samples included 73 children from 5 kindergartens in Padang City, Indonesia, as well as 51 kindergarten teachers.

Methods: The research method used was research and development (R&D) with the ADDIE model. The ADDIE model includes the five phases of ADDIE. Data were obtained from surveys, interviews, observations and documentation.

Results: The study revealed three main findings: (1) Teachers require augmented reality (AR) media on the theme of ecology, particularly floods and volcanic eruptions in science learning for EC. (2) The research has produced ETBARM content that is integrated and valid. (3) The implementation and evaluation of ETBARM, particularly floods and volcanic eruptions, can enhance EC science abilities.

Conclusion: In conclusion, the ETBARM, particularly the topics of floods and volcanic eruptions, effectively enhances EC science abilities, including knowledge, process skills and scientific attitudes.

Contribution: This study supports the principles of science learning, which contributes to the extant body of knowledge regarding the positive impact of AR media on science abilities when applied to ecological themes, particularly floods and volcanic eruptions, highlighting its uniqueness and scientific contribution.

Keywords: ecological education; augmented reality; early childhood education; science learning; disaster education.

Introduction

Early childhood (EC) is a crucial period in the development of fundamental scientific learning. This is not limited to curiosity but includes systematic observation and a basic understanding of natural phenomena, which collectively form the foundation for lifelong educational engagement (Duncan, Magnuson & Shonkoff 2018). However, a significant number of young children still face challenges in acquiring adequate scientific knowledge and procedural skills during a critical developmental stage (O'Keeffe, Pather & Conley 2022). This situation underscores the urgent need to enhance EC science education through innovative and contextually relevant pedagogical strategies.

These early scientific experiences are important for fostering cognitive development and inquiry-based thinking and can spark curiosity and develop critical thinking skills. Engagement in learning at an early age plays a crucial role in shaping scientific reasoning, enhancing observational skills and fostering environmental awareness (Kaya & Ahı 2025; Morrison 2021). In general, basic science concepts are divided into four related studies, namely physics, biology, environment and universe (Yaswinda 2019; Dodge, Colker & Heroman 2002). In addition, these principles are also linked to the disciplines of ecology and technology (Jackman 2012). Children's science abilities

Note: Additional supporting information may be found in the online version of this article as Online Appendix 1.

include knowledge, process skills and scientific attitudes that enable them to explore and build an understanding and interaction of the natural environment (Yaswinda 2019; Brewer 2007; Charlesworth & Lind 2010; Jackman 2012).

The repercussions of ecological degradation are already being experienced by the human population (Raharja 2014). It is therefore recommended that education with an ecological focus be implemented in EC education, as it has been demonstrated to assist children in expanding their knowledge and fostering awareness of novel perspectives on the management of the Earth (Yaswinda 2019). The introduction of ecological concepts through natural disasters (floods and volcanic eruptions) has been demonstrated to facilitate children's comprehension of the consequences of human actions on the environment, encompassing both positive and negative outcomes. While volcanic eruptions are considered a natural phenomenon, the ecological implications of such events for human life are a subject that is taught in schools. The role of ecology in the prevention and exacerbation of flood disasters is a subject that has been widely documented.

Education for sustainable development in EC places significant emphasis on ecological awareness and action. The integration of ecological content, such as recycling, biodiversity and environmental concerns, into play-based learning has been demonstrated to foster curiosity and empathy towards nature (Davis 2015). Moreover, ecological themes offer a tangible relevance to the real world, thereby enhancing children's comprehension of scientific principles and the interconnected nature of life systems. The comprehension of ecological concepts by children is also influenced by teachers' limitations in providing interactive and contextual learning media (Hardiyanti, Arif & Sulkify 2024). The problem of EC science learning is the teacher's lack of ability to provide exciting science content for children (Eliza et al. 2024).

The potential of augmented reality (AR) technology to transform abstract concepts into concrete experiences through interactive three-dimensional visualisations has been extensively researched. When combined with AR, these themes become more immersive and engaging (Avila-Gazon et al. 2021), opening new opportunities for experiential learning in EC science education. Children's interaction with the environment is important. In this context, AR is a promising educational media that combines digital elements with the real-world environment, providing interactive, immersive and developmentally appropriate experiences for young learners (Akçayır & Akçayır 2017; Chen 2020). It helps young children visualise and understand abstract scientific concepts (Chen 2020; Ziden, Ziden & Ifedayo 2022).

Empirical studies have shown the potential of AR to enhance children's motivation, understanding and cognitive learning in the domain of science education (Altınkaynak & Özel 2024; Ladykova et al. 2024). For example, Altınkaynak and Özel (2024) documented substantial progress in scientific

understanding and engagement when AR media were used in EC education settings. In the South African context, Pan et al. (2021) explored the application of AR in the classroom and confirmed the potential to support language acquisition and cognitive development, despite challenges in implementation. These results collectively underscore the value of AR as a transformative educational tool in EC learning. The AR market in the education sector is projected to grow at an annual rate of 20.8% until 2024, showing strong prospects (Garzón et al. 2020).

However, few studies have integrated ecological education into AR media designed for EC science learning (Gestiada, Tisoy & Lasala 2025; Liu et al. 2023; Lo, Lai & Hsu 2021). Recent studies emphasised the importance of high-quality EC programmes that integrate cultural and ecological content to promote comprehensive development (Kontkanen et al. 2023; O'Keeffe et al. 2022). This gap can be addressed by designing, developing, implementing and evaluating ecological themes-based augmented reality media (ETBARM) for EC.

Although interactive media for ecological science have been developed for older students (Suryawati 2020; Wibowo et al. 2024), few studies target EC learners using AR. Children aged 5–6 years can understand fundamental ecological concepts through digital media (Helena et al. 2024), but the integration of AR with such content remains underexplored. This study contributes to the development of technology-enhanced sustainable learning in EC science education, with ecological themes, particularly floods and volcanic eruptions. This study was guided by the following research questions: *What are the results of the analysis of AR media needs for kindergarten teachers? How should AR media be designed and developed to support science learning related to ecology, particularly floods and volcanic eruptions for EC? Is the ETBARM, particularly floods and volcanic eruptions, that has been developed effective in improving the science abilities of EC?*

Based on the description above, this study aims to explain the analysis, design, development, implementation and evaluation (ADDIE) of the ETBARM, in science learning for EC. Specifically, the objectives are to: (1) analyse kindergarten teachers' needs for AR media appropriate for science and for presenting ecological content; (2) design and develop the ETBARM to foster science learning for EC; and (3) implement and evaluate the use of the ETBARM in science learning for EC.

Literature review

Early childhood education

Vygotsky's theory posits that children learn through social interaction, the existence of the Zone of Proximal Development and language as a developmental tool. The learning process, as defined by Vygotsky, can only occur when children interact and cooperate with their surrounding environment. Vygotsky's theory posits that the development

of the mind, language and social skills is supported and enhanced through interaction with others. The learning process is only possible when children interact and cooperate with their surrounding environment. Meanwhile, according to Piaget, children develop their intelligence through experience, the formation of schemes and the ability to adapt to the environment (Morrison 2021). Montessori believed that the absorbent mind is a time of great potential in terms of individual development. Humans require stimulation and opportunities to develop their brains through active learning and exploration, and improvement through the senses (Isaacs 2010).

Indonesia has set ambitious goals to achieve the Sustainable Development Goals (SDGs) by 2030, with a focus on accelerating the achievement of 169 targets spread across 17 goals, an effort that started in 2015. Early childhood education in Indonesia is a top priority within the SDGs framework, particularly Goal 4: Quality Education. The National Development Planning Agency of Indonesia has set specific education milestones to be achieved by 2030 (Amanah, Riyanto & Rizqullah 2023).

In line with this goal, EC education is recognised as a top priority in the SDGs. EC education plays an important role by fostering environmental awareness and a sense of responsibility in children from a formative age, particularly between the ages of 2 and 5. In the Indonesian context, there is a strong emphasis on religious and cultural values in society. The application of religious moderation in EC can be effectively facilitated in educational settings and at home, with active participation from parents. The EC phase is often referred to as the 'golden age', characterised by rapid developmental changes that are considered crucial because this period offers an optimal opportunity to enhance children's growth and development. In the Indonesian context, EC education is conceptualised as a series of initiatives aimed at holistic childcare from birth until the age of six, thereby offering educational stimulation designed to facilitate physical and spiritual development. This foundational stage plays a crucial role in preparing children for the more advanced phases of their educational journey.

Early childhood science learning

The development of science education in EC lays the foundation for lifelong learning and adaptability (Duncan et al. 2018). However, studies in Indonesia and other developing countries show that many EC education programmes are still unable to effectively integrate these domains (O'Keeffe et al. 2022). Science refers to the field of natural knowledge that comprises contextual understanding and procedural inquiry, through which children gain insights into nature and the phenomena while showing scientific dispositions during practice (Campbell & Howitt 2015; Uzokboev 2024). Early childhood science education integrates scientific process and content skills, including the ability to communicate core concepts related to physics, biology, Earth and environmental science, healthy living and the universe

(Yaswinda 2019; Trundle 2015). Science abilities include knowledge, process skills and scientific attitudes that enable children to explore and build an understanding and interaction of the natural environment (Yaswinda 2019; Brewer 2007; Charlesworth & Lind 2010; Jackman 2012).

This field of study is related to facts or truths organised systematically and shows the validity of general laws. Science is also understood as an effort to discover the essence of everything, which includes knowledge, attitudes and skills that enable individuals, including children, to solve various problems encountered in daily life (Yaswinda 2019). Although the curriculum emphasises early science literacy, many preschool educators face difficulties in conveying scientific content, specifically topics that are abstract or complex, such as natural disasters, environmental changes and conservation efforts (Greenfield et al. 2024; Park, Lim & Song 2024). These challenges are worsened by the lack of pedagogically appropriate teaching materials and limited opportunities for professional development in innovative teaching methodologies. Consequently, young learners often fail to develop fundamental scientific process learning, including observation, comparison and communication, which are crucial for future academic achievement and lifelong educational engagement.

Ecological themes in education

Education oriented towards ecology has become important and urgent, given that the world is already in ecological crisis. Ecological content provides real-world relevance that can deepen children's understanding of science and the interconnectedness of life systems. Ecological themes-based education for EC is learning that discusses local environmental issues and is integrated with activities in the form of (1) exploration and discovery activities; (2) interactions with plants and animals; (3) human interactions with the abiotic environment; and (4) activities that reduce damage to the Earth (Yaswinda 2019). The aforementioned relatedness to the Earth and the environment encompasses the environment around children, such as the sky, natural phenomena and protecting the environment (Dodge et al. 2002). The integration of ecological themes such as recycling, biodiversity and environmental concern into play-based learning has been shown to foster curiosity and socio-emotional empathy (Sithole 2020). In the South African context, environmental learning is increasingly being integrated into the curriculum through storytelling, outdoor learning and community-based projects (Fenech et al. 2022). When combined with AR, this content becomes more immersive and relevant, creating new possibilities for experiential learning (Wen et al. 2023).

Augmented reality in education

Augmented reality has become an increasingly relevant tool in EC education because of the ability to deliver interactive, engaging and multisensory experiences (Akçayır & Akçayır 2017). The applications help young children visualise abstract

concepts and enhance motivation, particularly in science education (Ziden et al. 2022). In a recent South African study, Westhuizen and Hannaway (2021) found that AR-supported games improved early language and cognitive engagement, underlining the potential beyond traditional learning methods. Similarly, previous studies have established that AR has the potential to enhance creativity, memory retention and active participation in classroom settings. A systematic review by Akçayır and Akçayır (2017) underscores the ability of AR media to create interactive learning environments that foster deeper engagement and improve memory.

In general, AR can present abstract science materials as concrete visualisations that are easy for children to understand (Chen 2020). The application in science learning is believed to enhance motivation, engagement and learning outcomes in EC (Altınkaynak & Özel 2024). When combined with an ecological approach, AR introduces contextual science concepts related to the living environment. Augmented reality media can increase interest, understanding and learning outcomes in science domains for EC. Altınkaynak and Özel (2024) found significant improvements in comprehension of science concepts through AR media. Aydoğdu (2022) also reported that AR can develop children's cognitive abilities and creativity. Pan et al. (2021) showed that AR use in EC classrooms enhanced understanding and memory retention, although technological integration challenges required teacher training. However, these studies remain limited to rural areas. Augmented reality interactivity is consistent with the developmental needs of young children who learn best through active exploration (Chang et al. 2022). The flexibility also allows content to be personalised and localised, essential in diverse educational settings such as Indonesia.

Gaps in the literature and study contribution

Despite the significant evidence endorsing the application of AR media in EC education, only a few studies have examined the incorporation of ecological themes to promote scientific learning within a unified framework. The prevailing studies predominantly concentrate on cognitive advancement outcomes. Furthermore, investigations that are context-specific, specifically those emanating from Southeast Asia, are significantly scarce. This study intends to address the deficiency by developing and assessing AR media infused with ecological content to advance scientific development in EC. It leverages exemplary practices from the Global South and makes a significant contribution to the burgeoning field of sustainable, technology-enhanced learning for young learners. Therefore, there is a pressing need for media that effectively supports EC education.

The originality of this study is rooted in the creation of AR media meticulously designed to bolster the young children's scientific learning through content grounded in ecological themes. This advancement is manifested in the incorporation of AR technology, presenting materials related to floods and volcanic eruptions, which can be readily accessed by children

using laptops and smartphones. The resultant media provides an avant-garde solution that introduces a novel dimension to digital pedagogy for EC inherently engaging and developmentally significant. Presently, no existing studies have exclusively examined the ETBARM for EC, particularly using themes of floods and volcanic eruptions, thereby underscoring the uniqueness and scholarly contribution.

Research methods and design

A research and development (R&D) approach was used based on the ADDIE instructional design model, which includes five sequential phases, namely analysis, design, development, implementation and evaluation (Branch 2009). The ADDIE framework was selected because of its systematic nature, making it highly suitable for the development of innovative learning media, such as AR applications focused on education (Molenda 2015). The ADDIE model is one such instructional design model. This model has been used to develop curricula in various fields, such as library instruction (Reinbold 2013), the Picture Science Story application (Eliza et al. 2024) and to develop an intelligent virtual reality interactive system for learning pour-over coffee brewing (Yu et al. 2021).

This study was conducted in the city of Padang, with 48 teachers in the initial survey. It should be noted that the 10 teachers participating in the analysis also took part in the Focus Group Discussion (FGD) and Training of Trainers (ToT). Phase implementation included five kindergartens with a population of 187 children and 19 EC teachers. The sample consisted of 73 children and 11 teachers, selected through purposive sampling based on developmental readiness and access to the basic technology required for AR interaction. Sampling was selected based on the criteria of children aged 5–6 years and parents who agreed to their children becoming research subjects by collecting informed consent. The kindergarten population showed age variation, and there were some children whose parents did not give their consent for them to participate in this study.

Sampling was conducted using purposive sampling. For the survey at the analysis stage, questionnaires were distributed, and after 1 week, 48 teachers spread across the city of Padang.

Phase 1: Analysis

In the analysis phase, data were collected through a literature review to examine the importance of EC science learning, the relevance of ecological themes-based content and the potential of AR media. This review supported learning innovation, validated performance gaps, determined appropriate learning objectives and identified the resources needed for media development. To complement the literature results, a needs analysis was conducted by distributing Google Forms to EC educators in Padang City. This step aimed to confirm the characteristics of the target audience

and identify suitable AR media ecology topics needed by teachers. This study was conducted in the city of Padang, with 48 teachers in the initial survey.

Phase 2: Design

Learning objectives were formulated in line with the Indonesian EC Education Curriculum and disaster education guidelines. This phase was a conceptual design that underlined the subsequent development process. At this phase, the research team focused on integrating natural disaster scenarios (volcanic eruption and flood), safety procedures and environmental impacts into an interactive AR media, using the *Assemblr* Studio platform digital content. Instrument design was also carried out at this phase, adapted from Charlesworth (2016), Brewer (2007); Jackman (2012), Yaswinda (2019), as shown in Table 1.

Phase 3: Development

The development process utilises *Assemblr* Studio to create AR media, facilitating the incorporation of marker-based 3D visualisations. These visualisations enable children to scan markers with mobile devices and access interactive science learning experiences. Augmented reality content is utilised to present key scientific phenomena associated with natural disasters, including volcanic eruptions and floods, in a manner that is developmentally appropriate and visually engaging. Interactive features have been incorporated to facilitate the observation of cause-and-effect relationships by children, the identification of natural elements and engagement in basic scientific reasoning.

Following the completion of the ETBARM prototype, the subsequent phase involved media validation, which entailed the involvement of four experts: two in the field of EC education and two in the domain of educational technology. The ETBARM prototype trial was conducted in two stages. A one-to-one interview was conducted with a kindergarten teacher. This was followed by an FGD involving 10 teachers from five kindergartens. This activity aimed to gather feedback on the AR media being developed for EC science learning, select or design supporting media and develop learning guides for teachers. Following this, the AR media prototype was revised. Furthermore, a small-scale trial was

conducted involving three kindergarten teachers and 15 kindergarten children. The objective of the trial was to produce a science learning guidebook on ETBARM. The results of the trial and the revised guidebook are presented hereafter.

Phase 4: Implementation

The implementation phase began with ToT for 10 kindergarten teachers. This ToT was necessary for the implementation of science learning with ETBARM, as well as to adequately prepare students in the application of this media. Furthermore, a formative trial in the form of a field trial was conducted in five kindergartens involving nine kindergarten teachers who had participated in the ToT and 48 kindergarten students. One teacher who had participated in the ToT did not take part in this field trial because of health reasons. In this field trial, students participated in group learning. There was one group with one teacher. Each session focused on science themes related to volcanic eruptions and floods. The ETBARM was accessed via laptops and smartphones available in the classroom environment. During these sessions, the behavioural responses and engagement levels of the students were meticulously documented. Additionally, qualitative data were obtained through interviews with teachers and children. Concurrently, quantitative data were obtained through pre-test and post-test observations instruments.

Phase 5: Evaluation

In the final phase of the ADDIE framework, the effectiveness of the ETBARM intervention was evaluated. Scientific progress was quantified using pre-tests and post-tests observation instruments and educator reflections. The quantitative data were analysed using a range of descriptive and inferential statistical methods, including the Wilcoxon Signed Rank Test, to measure the impact of ETBARM on students' science abilities. Qualitative data from teacher and child interviews, as well as observation results, were analysed. Additionally, a decision tree model was used to identify predictors of learning outcomes (Online Appendix 1).

Ethical considerations

Ethical approval was obtained from the Research Ethics Committee of Padang State University (Approval No. 008/KEPK-UNP/5/2025). Participants were asked for their written informed consent, which assured their safety during participation as well as no risk or harm of any sort, in compliance with the ethical requirements of the institution coordinating this study. The study was entirely optional, and participants were free to leave voluntarily.

Results

Phase 1: Analysis

The analysis phase yielded several key results. The literature review emphasised the importance of EC science education, particularly in relation to ecological themes. It underscored

TABLE 1: Instrument content outline of science abilities.

Dimension	Sub-variable	Indicator
Science content	Knowledge	The child can retell the content of the AR media display.
		The child can explain the causes of floods or volcanic eruptions.
Science process skills	Observing	The child mentions safety procedures during a flood or volcanic eruption.
		The child is able to observe the process of a flood or volcanic eruption through AR.
	Comparing	The child can compare the condition of a mountain before and after an eruption, or the environment before and after a flood.
	Predicting	The child can predict what might happen after a flood or volcanic eruption.
Scientific attitudes	Scientific attitude	The child shows curiosity towards the content presented in the AR media.

AR media, augmented reality media.

the instructional value of integrating AR to bridge existing performance gaps and improve the delivery of science content in EC settings. This review also emphasised the need for contextually relevant, engaging and developmentally appropriate digital media to support children's understanding of complex natural phenomena. A needs analysis conducted through an online Google Form survey with 48 teachers of EC education showed that AR media was rarely used in schools, as shown in Table 2. The proportion of female teachers was found to be 97.9%, while the proportion of male teachers was 2.1%. The proportion of teachers who hold qualifications at the Master's level is 35.4%, at the Bachelor's level 58.3% and at the Senior High School level 6.3%. The data indicate that 54.2% of respondents have accumulated between 10 years and 54 years of experience, 6.2% have accumulated between 5 years and 10 years, 16.7% have accumulated between 2 years and 5 years, and 22.9% have accumulated less than 2 years.

Based on the results, 72.9% of teachers have never used AR media in EC education. Twenty-one teachers were unaware of AR media previously, while the remaining were aware but unable to create media. The survey results also showed that AR media were widely used in developing EC science skills, including aspects of scientific knowledge, scientific process skills and scientific attitudes.

There was a scarcity of digital learning tools tailored to ecological topics, such as natural disasters. Table 2 presents the choice of respondents and shows that current resources were insufficient to explain abstract scientific events such as volcanic eruptions or floods in a way suitable for young learners. Additionally, there were difficulties in maintaining engagement because of a lack of interactive and visual materials. These results validated the need for the development of ETBARM specifically designed to develop EC science skills, including aspects of scientific knowledge, process skills and attitudes.

As part of the survey, educators were asked to select preferred topics for AR media development. The data generated show strong interest in themes such as volcanic eruptions (25.23%) and floods (21.20%). The analysis of topic preferences showed a striking tendency towards ecological phenomena that were urgent and contextually relevant to the environment. The graphical representation of these preferences emphasises the importance of designing educational media capable of

addressing the most pressing local issues, namely floods and volcanic eruptions, which received the highest scores among all the options presented. This shows a strong awareness or interest among children and teachers in topics directly related to natural disasters that frequently occur in the area.

The analysis showed a lack of contextual and digital learning tools that could effectively help children understand ecological phenomena such as natural disasters in an age-appropriate and engaging manner. Furthermore, many teachers reported difficulties in conveying science concepts related to events such as volcanic eruptions and floods because of the limited availability of visual and interactive learning materials.

Phase 2: Design

Figure 1 (a) and (b) present the design phase focused on the evolution of AR media in accordance with the requirements of the curriculum, which is in line with initiatives aimed at improving the effectiveness and calibre of information and communication technology (ICT)-integrated learning resource centres as mandated by the Ministry of Education and Culture of Indonesia.

Student's conceptual understanding and scientific process learning were significantly enhanced through the use of ETBARM. The development of this media was achieved through the application of *Assemblr* EDU or *Assemblr* Studio Web. This includes evaluations and critiques from educators and experts, as well as systematically designed 3D scientific content consistent with established learning objectives.

The ETBARM on the theme of flooding consists of 10 slides, with each one being used for approximately 1–1.5 min, resulting in a total learning time of around 15 min. As demonstrated in slides 1–2, the concept of flooding and its various causes is introduced, while slides 3–6 describe environmental factors such as forest burning, illegal logging, barren land and the habit of littering. Slides 7–8 illustrate high rainfall and flood conditions, while slides 9–10 demonstrate the evacuation process and the significance of maintaining environmental cleanliness. The ETBARM

TABLE 2: Level of augmented reality media and topics used in early childhood education.

Variable	Frequency	Results (%)
Use of AR Media in EC Education		
Never used	-	72.9
Have used	-	21.1
Disaster type		
Erupting volcano	25	23.0
Flood	21	20.0
Earthquake	20	19.0
Landslide	10	9.0

AR media, augmented reality media; EC, early childhood.

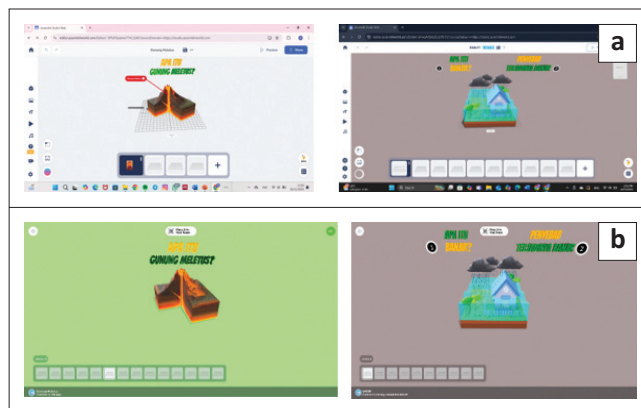


FIGURE 1: Augmented reality media development process with *Assemblr* studio (a) and display of the augmented reality media (b).

presentation on the subject of volcanic eruptions consists of 14 slides, with each one being used for approximately 2 min, thus resulting in a total learning time of approximately 28 min. The initial slides (1–2) provide an introduction to ETBARM and its utilisation. This is followed by the subsequent slides (3–5), which focus on the presentation of various mountains, including *Marapi*, *Singgalang*, and *Tandikek*. Slides 6–12 illustrate the gradual process of a volcanic eruption, commencing with the conditions that precede the eruption, the anatomy of the volcano and culminating in the ejection of eruptive material. The final two slides (13–14) present material on disaster mitigation and thus serve to conclude the lesson.

Phase 3: Development

Table 3 presents the Draft Design ETBARM, which was assessed by EC and instructional media experts. The ETBARM was evaluated by two instructional media experts using a structured rubric consisting of three main components, namely, content quality and objectives, instructional quality and technical quality. Each indicator was rated on a scale of 1–5.

Furthermore, both experts were granted the opportunity to submit notes regarding the validated AR media. The conclusion of the first expert stated that this media is very suitable for use in EC education. The second expert stated that there were some technical inconsistencies, but these did not significantly affect its usability, so ETBARM could proceed to the trial stage.

Furthermore, the FGD results showed several suggestions for improving media, including the need to add an initial explanation about the types of natural disasters, whether caused by human actions or natural phenomena, the use of real mountain images for greater realism and the addition of lava flood content to enrich the material. Teachers also suggested adding a disaster mitigation section at the end of the lesson as an effort to foster disaster-responsive attitudes

TABLE 3: Expert validation results of ecological themes-based augmented reality media.

Component	Indicator	Score
Content and objectives quality	Alignment with EC curriculum	5.0
	Relevance to children's developmental stage (5–6 years)	5.0
	Balanced integration of text, visuals and AR elements	5.0
	Proportional presentation of natural phenomena	5.0
Instructional quality	Child interactivity with AR content	5.0
	Motivational quality to stimulate curiosity	5.0
	Flexible use (independent or guided by a teacher)	5.0
Technical quality	Visual clarity and readability	5.0
	Attractiveness and accuracy of 3D visualisations	5.0
	Stability of the application	4.0
	Compatibility with various devices	5.0
Average	-	4.9

AR, augmented reality; EC, early childhood.

in children. Additionally, illustrations of children littering were added as part of education on behaviours that could trigger environmental disasters. Teachers also suggested adding a disaster mitigation section at the end of the lesson as an effort to foster disaster-responsive attitudes in children. Additionally, illustrations of children's littering were added as part of education on behaviours that could trigger environmental disasters.

As a follow-up, a special guidebook was developed for teachers to assist in the effective use of ETBARM in the classroom. This guidebook has been validated by two media and learning experts to ensure the suitability of the content and ease of use. Furthermore, an assessment instrument for EC science skills was developed, covering aspects of knowledge, skills and scientific attitudes. Following this, the AR media prototype was revised. In addition, a small-scale trial was conducted involving three kindergarten teachers and 15 kindergarten children with the code AK. During this small trial, the system functioned effectively, with minimal disruption to the utilisation of ETBARM. In the study, teachers employed a combination of one laptop and one mobile phone as aids. The composition of the group is as follows: there are five groups in total, with each group consisting of three members.

During the activity, the researchers asked the children to try the ETBARM in turns. All the children appeared enthusiastic about observing the use of AR media in front of the class. During ETBARM practice, the children demonstrated a high level of curiosity. They observed the flood visualisations appearing on the device screens and began connecting them to the explanations provided earlier. While waiting for their turns, children remained focused and occasionally commented on what they saw. Overall, the learning atmosphere was active, orderly and conducive. Technical challenges, such as a shortage of devices and network signal disruptions, occurred during the use of ETBARM, but the children patiently waited until the media functioned normally again. At the end of the session, some children were able to explain the causes and effects of flooding based on what they observed through the ETBARM.

The learning process proceeded in an orderly fashion; however, a revision to the guidebook was subsequently issued. The previous edition of the guidebook stipulated that the composition of each group should be two to three children. Following a small-scale trial, the protocol was revised to stipulate that each group should comprise four children with one piece of equipment, a laptop or a handphone.

Phase 4: Implementation

The implementation phase included ToT activities and small classroom trials. Training of Trainers activities were provided to kindergarten teachers as prospective users of AR media to help understand how to operate media, use the guidebook and effectively integrate content into EC science education.

During the ToT, teachers provided suggestions regarding the guidebook for using ETBARM with a laptop through a link.

The field trial occurred over four meetings at four kindergartens (BK, CK, DK and EK) located in Padang City. During this phase, the children participated in learning activities in small groups facilitated by educators who had received special training. Sessions one and two focused on the science theme of melting mountains, while three and four focused on the theme of flooding. The activity started with the teacher explaining the material as an introduction to build children's awareness about the importance of understanding the topic being studied before using AR media. Subsequently, the children were divided into small groups to explore directly using laptops and smartphones available in the classroom. The ETBARM allowed children to make three-dimensional visualisations and actively interact with the scientific phenomena shown, in accordance with the cognitive development stage. The results of observations and semi-structured interviews at four kindergartens are presented. The following essay will explore the implementation of AR media in the classroom.

The implementation of ETBARM in four kindergartens proceeded in a satisfactory manner, successfully capturing the attention of the young learners. To address these issues, teachers employed a range of management strategies. BK employed a projector and provided lucid explanations; CK orchestrated group activities; DK surmounted equipment and initial heat-related challenges; and EK meticulously prepared the devices through structured, turn-based sessions. The overall experience of ETBARM learning was found to be engaging and well-managed.

Secondly, the challenges encountered must be addressed. The primary challenges encountered pertained to device constraints and the unreliability of internet connections. The occurrence of delays in the BK and CK cases was attributed to limitations inherent in the utilisation of smartphones. The DK case exhibited suboptimal connectivity, a factor that exerted a negative influence on the children's patience levels. The EK case involved the incorporation of additional devices to mitigate signal-related challenges. Teachers successfully addressed this issue by implementing a systematic approach to scheduling, establishing age-appropriate groups and offering a variety of engaging activities.

Thirdly, consideration must be given to the responses of children. The children demonstrated a notable level of enthusiasm, curiosity and active participation. The study found that ETBARM learning was perceived as more enjoyable than traditional methods, with some participants even assisting their peers. Teachers noted a lively and interactive classroom atmosphere.

Phase 5: Evaluation

After the implementation was completed, an evaluation phase was conducted through an FGD with the team members directly participating in the implementation process

in the field. In this discussion, each individual presented their respective observations during the implementation of learning using ETBARM in the classroom. The first participant showed that the use of AR media required a stable internet signal. In some sessions, children had to wait quite a long time because the media loaded slowly, primarily because of a poor signal or devices with full storage capacity. The second participant also emphasised the same constraints, namely the limited number of devices available at the school and the poor quality of the internet network, which hindered the smooth use of media. The third participant confirmed similar results, adding that the technological infrastructure at the partner kindergarten was still inadequate to support the optimal use of AR media. Children's EC science abilities were assessed using a pre-test and post-test observation instrument obtained from observations made by teachers and the research team. On the first day of the field trial, pre-test data were obtained, and on the last day of the field trial, post-test data were obtained. The table of scores obtained is included in the Online Appendix 1.

The results showed that there was a significant enhancement in the mean score, escalating from 22.18 in the initial to 28.75 in the subsequent evaluation. This suggests that ETBARM has a positive effect on children's science understanding. The increment of 6.57 points underscores the efficacy of media in presenting content tangibly and engagingly. To evaluate the significance of the difference between pre-test and post-test scores, a Wilcoxon Signed Ranks Test was used (Table 4a and Table 4b). This non-parametric test was selected because of the paired nature of the data and the absence of normal distribution.

The empirical results demonstrated a statistically significant enhancement in the scientific learning outcomes following the implementation of ETBARM. The findings revealed that all 58 participants demonstrated elevated post-assessment scores in comparison to their initial assessment scores. The positive ranks equalled 45, the negative ranks equalled zero, and the ties equalled 13. This result suggests a consistent improvement in academic performance across the entire cohort. The Z-value of -6.637, when considered in conjunction with a significance level of $p = 0.001$, provides substantial evidence to support the hypothesis that the intervention had a significant and uniform positive influence on the

TABLE 4a: Distribution of Wilcoxon signed-rank test results.

Ranks	<i>n</i>	Mean rank	Sum of ranks
Post-test – Pre-test			
Negative ranks	0†	0.00	0.00
Positive ranks	45‡	23.00	1035.00
Ties	13§	-	-
Total	58	-	-

†, post-test < pretest; ‡, post-test > pretest; §, post-test = pretest.

TABLE 4b: Wilcoxon signed-rank test statistics.

Test statistics‡	Post-test – Pre-test
Z	-5.862†
Asymp. Sig. (2-tailed)	0.001

†, Based on negative ranks; ‡, Wilcoxon signed ranks test.

conceptual comprehension of scientific subjects. To ascertain the significance of the discrepancy between the pre-test and post-test scores, a Wilcoxon Signed Ranks Test was employed (see Table 4a and 4b). The selection of this non-parametric test was made on the basis of the paired nature of the data and the absence of a normal distribution.

During the implementation of ETBARM within the classroom context, qualitative analyses and expert evaluations showed a variety of beneficial effects on children's engagement and developmental processes. Participants showed an increased sense of curiosity and enthusiasm while interacting with the AR content, specifically during the scanning of markers and the observation of dynamic simulations of natural phenomena, including volcanic eruptions and floods. This immersive experience not only captivated attention but also augmented the capacity to articulate scientific occurrences in coherent sequences, thereby showing enhanced conceptual comprehension. Media also facilitated peer interaction, as children assisted one another in using the technology, exchanged insights and participated in group dialogues and communicative learning. Additionally, the lifelike visuals and interactive components of media contributed to increased emotional engagement and enhanced focus on learning. Children showed responses characterised by concern, empathy and excitement, linking the environmental scenarios to personal experiences. These interactive engagements fostered inquiry-based learning by stimulating behaviour such as questioning, predicting and reflecting. In summary, the integration of AR media not only advanced children's scientific knowledge but also cultivated socio-emotional growth and collaborative learning abilities in a significant and age-appropriate manner.

The findings demonstrated that the group utilising projectors attained notably higher gain scores in comparison to the kindergarten that exclusively employed ETBARM without projectors. This finding indicates that the presence of projectors can enhance the effectiveness of ETBARM by magnifying visualisations, allowing children to see digital objects more clearly and together, while simultaneously overcoming the limitations of the number of devices. Pre-test and post-test science abilities were obtained from the observations of teaching staff and the research team. These were then compared between classes that used projectors and classes that did not use projectors. The study found that there were 33 children in classes that used projectors and 25 in classes that did not use projectors. The findings indicated a substantial discrepancy between the two groups, with the projector-utilising classes demonstrating a higher level of performance. The statistical test is demonstrated in Table 5a and Table 5b.

Discussion

The utilisation of ETBARM within the domain of EC education has, in general, proven to be a successful endeavour. It is evident that educators have the capacity to employ AR media as a medium to present scientific principles

in a manner that is more appealing and interactive. A variety of strategies are employed, including the utilisation of AR media objects displayed via projectors, the segmentation of children into smaller groups and the provision of both simple and structured instructions. This pedagogical approach has been shown to facilitate the comprehension of material by children, thereby enabling them to maintain concentration during activities (Smith et al. 2023). The integration of AR media has been demonstrated to enhance the learning experience, stimulating curiosity and promoting intrinsic motivation in children. This finding is consistent with the conclusions of Altmeyer et al. (2020), who emphasised that AR-based visualisation can provide contextual support, reduce cognitive load and enhance children's conceptual understanding. Moreover, these findings serve to reinforce the perspective of Jacob, Warde and Dumane (2020) that the success of AR is not solely determined by the sophistication of its technology, but rather by the teacher's pedagogical strategies in facilitating learning interactions.

The implementation of ETBARM in educational settings presents a number of challenges for educators. The primary challenges encountered pertain to the constraints imposed by the devices themselves, the limited storage capacity of these devices and the unreliability of internet connections. These conditions have the potential to impede the efficient execution of learning activities and prolong the waiting period for children awaiting their turn. To address this issue, educators have been known to implement a variety of strategies. These include the scheduling of turns, the formation of groups and the provision of activities for children to engage with during the waiting period. These strategies exemplify the adaptability of educators in addressing technological constraints, thereby facilitating the continuity of learning in spite of scarce resources. This finding is consistent with the conclusions of Garzón et al. (2019), who, in their meta-analysis, emphasised that the effectiveness of AR is closely related to technical readiness and infrastructure support. This viewpoint is further reinforced by Jacob et al. (2020), who demonstrated that external factors and the readiness of the learning environment are important variables in the successful implementation of AR.

The response of children to ETBARM on science learning was very positive. It was evident that the participants

TABLE 5a: Tests of normality for gain scores.

Tests of normality	class	Kolmogorov–Smirnova			Shapiro–Wilk		
		Statistics	df	Sig.	Statistics	df	Sig.
Gain score	Projector	0.172	33	0.015	0.912	33	0.011
	Non-projector	0.329	25	0.000	0.740	25	0.000

TABLE 5b: Mann-Whitney *U* test results for gain score difference.

Test statistics	Gain score
Mann–Whitney <i>U</i>	69 000
Wilcoxon <i>W</i>	394 000
<i>Z</i>	-.5462
Asymp. Sig. (2-tailed)	0.000

exhibited a high level of enthusiasm, a profound sense of curiosity and a notable degree of active involvement at every stage of the activity. It was evident that the students derived pleasure from the learning experience, as evidenced by their willingness to assist their peers in navigating the device's functionalities. The classroom atmosphere is characterised by heightened levels of interaction and enthusiasm, which contribute to an enjoyable learning environment. This response suggests that ETBARM not only enhances children's attention but also supports their social and emotional development through collaboration and positive interaction with peers. These findings are consistent with those reported by Kaur, Mantri and Horan (2020), who emphasised that collaborative AR-based learning design can enhance social engagement and learning motivation. In accordance with the aforementioned points, Altmeyer et al. (2020) concur that interactive visualisation through AR has the capacity to enhance children's learning experiences and ensure sustained engagement throughout the activity.

Interviews with teachers at the four kindergartens showed that the use of ETBARM among young children was well received, sparking enthusiasm, curiosity and active engagement. Despite challenges such as weak internet signals and limited devices, the children still demonstrated high enthusiasm, indicating that the novelty effect of ETBARM is quite strong. This aligns with the concept of perfectly situated scaffolding, which helps reduce cognitive load (Bower et al. 2014). Strategies such as small group division, direct examples from teachers and good activity management supported the effectiveness of ETBARM use. This collaborative approach was proven to stimulate social interaction and increase student engagement (Çakıroğlu et al. 2022; Masneri et al. 2022). Limitations in devices and unstable internet connections caused children to wait, yet enthusiasm remained high. This aligns with a meta-analysis showing a moderate effect on learning outcomes ($d \approx 0.68$), meaning that despite less-than-ideal technical conditions, learning motivation remained intact (Garzón & Acevedo 2019). The most optimal outcomes, achieved when children interact with teachers who act as facilitators, highlight that pedagogical support is more crucial than technological sophistication (Sharma et al. 2022; Thangavel, Sharmila & Sufina 2025).

These quantitative results align with the constructivist approach, which emphasises the importance of active and meaningful learning through direct experience. The results of this study indicate that the use of ETBARM significantly improves science competence in EC. The average increase in science literacy scores was 6.57 points, from 22.18 in the pre-test to 28.75 in the post-test, supported by the Wilcoxon Signed Ranks test, which showed high statistical significance with a Z-value of -6.637 and $p = 0.001$ (Table 4b). These findings confirm that interventions using AR have a consistent positive effect on children's understanding of scientific phenomena such as floods and volcanic eruptions.

Integrating enables the visualisation of abstract concepts, such as cause-and-effect relationships in natural disasters, which are typically difficult to convey through conventional learning materials (Altınkaynak & Özel 2024; Ziden et al. 2022). Through this immersive experience, children can observe dynamic simulations, predict consequences and compare conditions before and after natural events, thereby optimising the development of their observation and classification skills – key components in early science learning (Charlesworth 2016).

In addition to quantitative data, classroom observations and interviews with teachers provide a deeper understanding of children's enthusiasm and engagement during learning using ETBARM. Teachers reported that students demonstrated curiosity, high spirits and joy, especially when ETBARM visuals were displayed. This affective response not only increased learning interest but also encouraged collaboration among students, where they helped each other and actively participated in class discussions. Some students were even able to recount their learning experiences and demonstrate scientific attitudes such as asking questions and making predictions.

Teachers' experiences during training and implementation of ETBARM also contributed to the success of this learning process. Although 72.9% of teachers had never used AR media before (Table 2), the training and trials conducted provided them with the confidence and pedagogical strategies needed to integrate this media into the teaching and learning process. The validation of the media, which showed an average score of 4.9 out of 5, confirms the quality of the content, instructional design and technical performance of this media (Table 3). These findings align with the principles of the science, technology, engineering, arts, and mathematics (STEAM) framework (Kewalramani & Havu-Nuutinen 2023), which emphasises the importance of integrating STEAM education from an early age.

Compared to previous studies, this research strengthens the evidence that AR effectively enhances science learning (Avila-Garzon et al. 2021; Ladykova et al. 2024), while introducing an ecological dimension that is still relatively under-researched, particularly in EC education (Gestiada et al. 2025). Unlike the focus on cognitive skills or the use of VR in higher education (Chang et al. 2022), this study demonstrates how AR environments can encourage scientific inquiry, foster empathy for nature and make learning enjoyable at the same time. Furthermore, this study responds to the agenda of developing digital learning in EC education (Kontkanen et al. 2023) by showing how interactive technology tailored to children's development can support the development of basic STEAM skills. The chosen ecological themes – floods and volcanoes – reflect local relevance while supporting the principle of enjoyable mobile learning (Pan et al. 2021), enabling children to explore important real-world phenomena in an age-appropriate format.

The study provides empirical support for the development and use of ETBARM as a viable innovation in EC education. By addressing science domains simultaneously, this intervention contributes to a more integrated and sustainable approach to early learning. This technology has been proven to enhance engagement, understanding and scientific skills such as observation and classification (Ahied et al. 2020; Setiawaty et al. 2024). Augmented reality media is also consistent with the developmental needs of young learners who benefit from hands-on and exploratory learning (Annisa & Subiantoro 2022; Papadakis, Kalogiannakis & Zaranis 2021).

It is interesting to note that, despite the absence of any specification in the research design regarding the use of projectors, teachers in Kindergarten BK and Kindergarten EK demonstrated initiative in utilising projectors in ETBARM learning. The findings demonstrated that the group utilising projectors attained notably higher gain scores in comparison to the kindergarten that exclusively employed AR without projectors. This finding indicates that the presence of projectors can enhance the effectiveness of AR by magnifying visualisations, allowing children to see digital objects more clearly and together, while simultaneously overcoming the limitations of the number of devices. Moreover, the utilisation of projectors fosters the establishment of a collective learning environment, where children are able to observe, respond and interact with one another. This perspective is in alignment with that of Vygotsky, who placed significant emphasis on the role of social interaction in the context of cognitive development. From a pedagogical perspective, this teacher initiative demonstrates that technological innovation alone is insufficient without creative mediation from educators. Consequently, the integration of projectors can be regarded as an effective form of scaffolding that enhances the benefits of AR in EC education.

Overall, the AR media developed with an ecological theme and designed using the ADDIE model proved effective in enhancing EC scientific abilities, including aspects of scientific knowledge, process skills and attitudes. The use of immersive digital content tailored to children's developmental stages enables them to observe, compare, communicate and understand scientific ideas more deeply. These findings confirm that the integration of environmental AR media in EC classrooms not only strengthens science learning but also contributes to the development of 21st-century skills and sustainable digital practices in education. Therefore, the development of similar innovations needs to be expanded to various learning contexts, especially in areas with limited access to conventional science learning resources.

Conclusion and recommendations

In conclusion, ETBARM, particularly the topics of floods and volcanic eruptions, effectively enhances EC science abilities, including knowledge, process skills and scientific attitudes. The utilisation of the structured ADDIE model

facilitated a systematic and developmentally appropriate design process, tailored to the needs and interests of this study. The present study underscores the viability of integrating ecological themes into AR media as a promising strategy to bolster EC education advancement in the scientific realm. It was expressed by kindergarten teachers in Padang City that there was a high level of enthusiasm for the necessity of AR media in EC learning. The development and implementation of an AR application grounded in ecological principles has been demonstrated to engender substantial enhancements in children's comprehension of environmental science.

The developed AR media was found to be both valid and effective in its function of bridging the gap between abstract scientific concepts and concrete learning experiences. It was determined that the media offered developmentally and culturally relevant content, engaging learning. Teachers' responses to the media were positive, with recognition of its value accompanied by identification of challenges related to infrastructure and digital readiness. These concerns underscore the necessity for targeted training and policy support to facilitate more widespread implementation.

The findings of this study suggest that the use of projectors in ETBARM has the potential to amplify AR's positive effects, particularly in increasing engagement, collective understanding and learning outcomes. These findings provide a foundation for further research to explore how the combination of AR and supporting visual media (e.g. projectors or large screens) can be optimised in EC education. This study makes a significant contribution to the expanding corpus of knowledge on the utilisation of AR media technology in the domain of engineering education, with a particular focus on the subjects of ecology and sustainability. This underscores the importance of holistic learning environments that simultaneously address cognitive needs.

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CRedit authorship contribution

Yaswinda Yaswinda: Conceptualisation, Methodology, Funding Acquisition, Investigation, Writing-original draft, Writing – review & editing. Yanti Fitria: Methodology, Visualisation. Nurhafizah: Data curation, Formal analysis, Validation. Zulminiati Zulminiati: Formal analysis. Windi Elsa Putri: Project Administration, Software, Writing – original draft. Dhea Meichika: Data curation, Software.

All authors reviewed the article, contributed to the discussion of results, approved the final version for submission and publication, and take responsibility for the integrity of its findings

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Data availability

The data that support the findings of this study are not openly available because of confidentiality, and are available from the corresponding author, Yaswinda Yaswinda, upon reasonable request.

Disclaimer

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