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Development of augmented reality media in science education on the topic of earth and the solar system

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Abstract: This study aimed to develop and evaluate Augmented Reality (AR)-based learning media for the Earth and Solar System topics in middle school science education. Using the Research and Development (R&D) approach with the ADDIE model (Analysis, Design, Development, Implementation, and Evaluation), the study developed AR media designed to enhance student understanding of complex scientific concepts. The effectiveness of the AR media was assessed through Aiken's V validation, practicality tests from teachers and students, and pre-test and post-test evaluations. The results showed that the AR media significantly improved student engagement, understanding, and academic performance. Aiken's V validation scores for usability, information, and interaction quality were above 0.8, indicating that the media was valid and effective. The practicality test revealed that teachers rated the media highly (93% usability), while students gave slightly lower ratings (81% usability). The N-gain score from pre-test and post-test evaluations showed a 56.2% improvement in students' knowledge, confirming the positive impact of the AR media on learning outcomes. Despite the challenges with usability for some students, the overall feedback supports AR's potential in enhancing science education, especially in rural settings. The study recommends further research to overcome usability challenges and optimize AR's classroom integration.

Keywords: augmented reality; learning media; earth and solar system; middle school; science education; student engagement

1. Introduction

In the rapidly evolving technological landscape, education has increasingly adopted technological tools to enhance learning. Technology helps achieve educational goals and plays a crucial role in advancing education within a country (Dritsas & Trigka, 2025; Kalyani, 2024). It involves people, processes, ideas, and tools to analyse problems, identify solutions, and manage learning solutions (Alasadi & Baiz, 2023; Alenezi, 2023). Technology integration in classrooms has significantly impacted the teaching and learning process by helping educators design, develop, and assess learning resources more effectively, leading to more interactive and efficient education (Marougkas et al., 2023; Onu et al., 2024). The learning process is closely tied to the interaction between students and teachers, with media playing a key role in delivering educational content (Rejeb et al., 2024; Zhao et al., 2023). Selecting the right learning media is essential in making lessons more engaging and interactive. Media can improve teaching quality and increase student motivation. Therefore, teachers must carefully consider learning objectives, student characteristics, and available resources when selecting media to ensure effective and enjoyable learning experiences (Mai et al., 2024; Wong & Hughes, 2023).

Among the emerging technologies, Augmented Reality (AR) has proven to be a promising educational tool. AR allows students to interact with real-world content by integrating computer-generated images into the environment, providing a more immersive and detailed learning experience (Al-ansi et al., 2023; AlGerafi et al., 2023; Iqbal et al., 2022; Kamińska et al., 2023). This technology is beneficial for teaching complex concepts like the solar system and Earth, which are challenging to convey through traditional

media like pictures and videos (Lan et al., 2021; Mansour et al., 2025). At SMP Negeri 1 Tigo Nagari, Earth and Solar System topics are taught with limited media, such as pictures and videos, which often fail to communicate abstract concepts effectively. This limitation has led to lower student performance in related assessments, with only a few meetings the required learning criteria for these topics.

Table 1. Assessment scores for the earth and solar system chapter

Class	Completed	Not completed
VII.A	2	30
VII.B	3	29
VII.C	2	30
VII.D	3	29
VII.E	2	30

SMP Negeri 1 Tigo Nagari, located in Pasaman Regency, follows the 2013 curriculum for Grade IX and the Merdeka curriculum for Grades VII and VIII. The school offers various subjects, including Science (IPA), which covers physics, chemistry, biology, and astronomy. However, based on the researcher's teaching experience, the media used for teaching the Earth and Solar System topics have mainly been limited to pictures and videos. These traditional media often fail to convey complex and abstract concepts effectively, leading to lower student performance. For instance, in the 2023/2024 academic year, only 2–3 out of 32 students in each class met the required learning criteria for the Earth and Solar System unit.

The researcher plans to develop AR-based learning media to address these challenges to enhance students' understanding. AR technology can provide interactive, 3D models of planets, allowing students to explore the Solar System from different perspectives, making learning more engaging and effective. Research has shown that AR-based media increases student engagement, understanding, and motivation (Ji et al., 2025; Mokmin et al., 2024; Y. Wang, 2022). Using AR for the Solar System will offer a more immersive and detailed learning experience. Several studies have explored the use of AR in education. A study by (Perifanou et al., 2023) highlighted the benefits of AR in making learning more interactive by integrating digital content with the real world. According to (Queida et al., 2023), the potential of Android-based AR applications in schools emphasizing their accessibility. Research by (Fitria, 2023) also confirmed the effectiveness of AR in both classroom and independent learning, as it helps students understand complex subjects better.

Many studies have explored augmented reality (AR) in education, but few have specifically examined its application in teaching the Earth and Solar System in middle school science classrooms. Moreover, there is limited research on how AR-based learning media can enhance student performance in science, particularly in rural areas such as Pasaman Regency. This research addresses this gap by developing AR-based learning media tailored to teaching the Earth and Solar System. The study seeks to answer three main questions:

RQ1. How can Augmented Reality (AR) be developed as a learning medium for the Earth and Solar System topic in middle school science education?
RQ2. To what extent does the use of AR-based learning media improve students' understanding of Earth and the Solar System concepts?
RQ3. How does AR-based learning media impact students' motivation and engagement in learning science?

By developing AR-based learning media specifically designed for teaching complex science concepts like the Earth and Solar System, this research contributes to the advancement of educational technology. It provides valuable insights into the effectiveness of AR in enhancing student understanding, engagement, and motivation. Additionally, the study offers practical recommendations for educators on implementing AR-based media in classrooms to improve learning outcomes.

2. Methods

This study uses the Research and Development (R&D) approach, a methodology to develop specific products and test their effectiveness (Daryanes et al., 2023; Suparno et al., 2019; Varadila et al., 2023). There are three types of R&D models: (1) Borg and Gall's development model, which involves ten steps and requires a long time to complete, (2) the 4D model, which is simpler and faster but stops at the dissemination stage without evaluating the product's quality, and (3) the ADDIE model, widely applied for developing educational products. The ADDIE model was chosen for this study due to its systematic approach and focus on product validation through analysis, design, development, implementation, and evaluation (Branch, 2009).

2.1 Procedure for AR media development

The ADDIE model consists of five stages: (1) Analyse identifying the causes of performance gaps, (2) Design verifying desired performance and testing methods, (3) Development creating and validating learning resources, (4) Implementation preparing the learning environment and engaging students, and (5) Evaluation assessing product and instructional quality before and after implementation (Branch, 2009). This study follows the ADDIE model to develop Augmented Reality (AR)-based learning media for teaching Earth and the Solar System in middle school science education. The development process follows the ADDIE model as outlined in Table 2.

Table 2. ADDIE model stages, objectives, procedures, and final products

ADDIE stage	Objective	General procedure	Final product
Analyse	Identify causes of performance gaps	Validate performance gaps, define learning objectives, understand the target audience, identify resources, and plan the project.	Analysis Summary
Design	Verify desired performance and testing methods	Inventory tasks, define learning objectives, and develop assessment strategies.	Design Plan
Development	Create and validate learning resources	Develop content, choose/develop AR media, create student and teacher guides, and conduct formative tests.	Learning Resources
Implementation	Prepare a learning environment and engage students	Prepare teachers and students and implement AR in the classroom.	Implementation Strategy
Evaluation	Assess the quality of the product and process	Define evaluation criteria, choose evaluation tools, and conduct evaluations.	Evaluation Plan

2.2 Subjects and research location

Based on the information provided in the text, the sample for this study consisted of 30 students from class VII.A at SMP Negeri 1 Tigo Nagari. This was reflected in the section discussing the needs analysis questionnaire, which was completed by 30 students from class VII. The research was conducted at SMP Negeri 1 Tigo Nagari, in Pasaman District, West Sumatra.

2.3 Data collection and techniques

This study employs qualitative and quantitative data collection methods to comprehensively understand the impact of the Augmented Reality (AR) learning media. For qualitative data, interviews and observations were conducted. Interviews were held with both teachers and students to gather in-depth insights into their experiences with the AR media (Annamalai et al., 2023; Romano et al., 2023). The focus was on understanding how the media influenced student engagement with the learning content and its perceived effectiveness in enhancing the learning process. Additionally, observations were made during the implementation of the AR media in the classroom (Monfared et al., 2022; D. Wang et al., 2021). This involved monitoring how students interacted with the technology, the level of their engagement, and any challenges or benefits that arose while using the AR media in their learning activities.

For the quantitative aspect, data were collected using questionnaires and tests. A needs analysis questionnaire was distributed to students to evaluate their perceptions of the necessity and effectiveness of AR-based media in their educational experience (Azzahra et al., 2024; Chang, 2021; Osorto Carrasco & Chen, 2021). This helped gauge whether students found the AR technology to be a valuable and relevant addition to their learning process. Practicality questionnaires were given to teachers and students to assess key factors such as AR media's usability, information quality, and interaction quality (Waskito et al., 2024). This feedback was essential in understanding how practical and user-friendly the AR media was in a real classroom setting. Furthermore, pre-test and post-test assessments were administered to measure students' knowledge before and after using the AR-based media (AlGerafi et al., 2023). The tests focused on the Earth and Solar System concepts, providing an objective measure of the improvement in students' understanding after using the AR media.

2.4 Data analysis

The collected data were analysed using both descriptive statistics and inferential statistics to provide a comprehensive evaluation of the AR media's effectiveness. For the needs analysis, the data from the questionnaires were analysed by calculating the percentage of students who agreed or disagreed with the necessity and effectiveness of the AR media (Chang, 2021; Sofianidis, 2022). This determined the consensus among students regarding the value of AR in enhancing their learning experience. The effectiveness and practicality of the AR media were evaluated by calculating the average scores from the practicality questionnaires (Kapp et al., 2022; Nelson et al., 2025). These scores were compared against established criteria for usability, information quality, and interaction quality, offering insights into the media's strengths and areas for improvement. To assess the impact of the AR media on student learning, the N-Gain method was applied to compare the pre-test and post-test scores. This method measured the normalized gain in student knowledge, clearly indicating how much students' learning outcomes improved after using the AR media.

The results were categorized based on the N-Gain scores, ranging from high to low improvement, offering a quantitative measure of the AR media's effectiveness in enhancing students' academic performance (Nandiyanto et al., 2022; Rahim et al., 2024). Combining qualitative and quantitative data, this research provided a well-rounded evaluation of the AR media's impact on students' learning experiences and outcomes.

3. Results

This study aims to develop an Augmented Reality (AR)-based learning media on the Earth and Solar System material by analysing the learning needs that underlie its development. The findings from this research were obtained through the ADDIE model development stages, which consist of five stages: analyse, design, development, implementation, and evaluation.

3.1 Analysis results

The analysis phase started with the learning needs analysis, analyzing the characteristics of the students, determining learning objectives, and reviewing the appropriate devices and platforms for AR. This analysis aimed to ensure that the developed media could enhance students' understanding of the material according to their needs. The results of the learning needs analysis were obtained by examining the teacher's teaching materials for the Earth and Solar System subject for grade VII students at SMP Negeri 1 Tigo Nagari. The curriculum analysis table can be found in Appendix 1. The learning needs analysis was further strengthened by interviews with colleagues and students. The conclusions from these interviews indicate that the teachers support the development of AR media as a tool to help explain lesson materials to students. Students showed high curiosity about using AR media in their learning.

Additionally, to ensure the students' readiness to use AR in learning, a questionnaire was distributed to 30 students to assess their readiness. The questionnaire consisted of 15 Likert-scale questions, with categories ranging from "Strongly Agree" to "Strongly Disagree." The results of this questionnaire, which are presented in Appendix 2, show that 88% of students strongly agree or agree that using AR media would benefit their learning. The learning objectives for the Earth and Solar System material were formulated by analysing the learning achievements. The material covered topics such as the solar system's structure, celestial bodies other than planets, Earth and its satellites, and the influence of the Sun on life. AR media was selected to facilitate students' understanding of this material, using the Assemblr Edu platform. The SWOT analysis for the learning media development is shown in the following Table 3.

Table 3. SWOT analysis for learning media needs

Aspect	Description
Strengths	1. High alignment with visual interactive media, such as AR. 2. 88% student approval for AR use. 3. Support from colleagues for AR development. 4. Assemblr Edu platform supports 3D media development.
Weaknesses	1. Not all students are accustomed to AR technology. 2. Required devices, such as smartphones or tablets, are unavailable for all students. 3. Teacher training is needed for effective implementation.
Opportunities	1. Digital technology in education fosters AR media integration. 2. AR media enhances student engagement and understanding of abstract concepts. 3. Useful for both self-directed and collaborative learning.
Threats	1. Unstable internet connection in certain areas. 2. Limited teacher time to adapt to new teaching media.

3.2 Design results (AR media storyboard design)

The design phase followed identifying the problem and analysing the learning needs. This phase culminated in developing key components, including the storyboard design, technical specifications for the AR media, and the learning modules. The primary goal of the storyboard design phase was to establish clear objectives for the AR learning media. The storyboard is a guiding framework for structuring the media, ensuring all elements align with the intended learning outcomes and providing a visual roadmap for the development process. This step is crucial in ensuring the media is pedagogically sound and visually engaging for students.

Figure 1.
AR Media storyboard design

a) Initial Screen
b) Main Menu
c) Learning Achievement and Purpose
d) Marker AR - Solar System
e) Learning Video - Phases of the Moon
f) AR Learning Media - Solar System (Interactive)
g) AR Learning Interface for Mercury
h) AR Learning Interface for the Solar System

Figure 1. AR Media Storyboard Design showcases the various stages and components of creating Augmented Reality (AR) learning media for the Earth and Solar System topic. The storyboard outlines the key elements for delivering an engaging and educational AR experience. Each section is carefully designed to ensure that students can interact with the content to enhance their understanding of complex astronomical concepts. The initial screen is the first interaction point, providing basic information such as the chapter title and a start button to initiate the learning module. Following this, the main menu offers easy navigation to various features of the AR module, including learning materials, quizzes, and additional resources. The learning achievement and purpose section clearly defines the learning objectives, setting

expectations for what students should achieve by the end of the module. This structure helps guide students through the content in a purposeful and goal-oriented manner.

The AR features include the Marker AR for the Solar System, which triggers 3D visualizations when scanned, offering an interactive and immersive learning experience. The learning video on the moon's phases further aids understanding by providing visual explanations. The AR Learning Media for the Solar System (Interactive) also allows students to explore celestial bodies and their characteristics hands-on. Specific interfaces are also designed, such as the AR Learning Interface for Mercury, which focuses on detailed information about the planet, and the AR Learning Interface for the Solar System, which provides a comprehensive, interactive overview of the entire Solar System, fostering deep engagement and learning. These elements together form a cohesive and dynamic AR learning environment.

3.3 Development results

The development of AR media using Assemblr Edu was conducted to address the challenges of low student understanding of the Earth and the Solar System. AR was chosen for its ability to present complex concepts interactively. Based on constructivist theory, active engagement enhances learning through interaction with the environment. Further results are depicted in Table 4 and Figure 2.

Table 4. Aiken's V validation for augmented reality

Assessed aspect	Validator			s1	s2	s3	∑s	n(c-1)	Aiken's V	Status
	V1	V2	V3							
Usability	5	4.375	4.375	4	3.375	3.375	10.75	12	0.9	Valid
Information Quality	4.75	4.125	4.125	3.75	3.125	3.125	10	12	0.83	Valid
Interaction Quality	5	4.625	4.125	4	3.625	3.125	10.75	12	0.9	Valid
Total	14.75	13.125	12.625	11.75	10.125	9.625	31.5	36	0.88	Valid

Table 4 presents the results of Aiken's V validation for the Augmented Reality (AR) media developed for the Earth and Solar System module. The validation was carried out across three assessed aspects: Usability, Information Quality, and Interaction Quality. The table shows the ratings from three validators (V1, V2, and V3), with each aspect evaluated on specific criteria, followed by the sum of scores (∑s), the number of respondents (n), and the final Aiken's V value. In terms of usability, the ratings from the three validators varied, with Validator 1 (V1) providing the highest score of 5, while Validators 2 (V2) and 3 (V3) provided slightly lower but still strong scores of 4.375. The overall sum of scores for usability was 10.75, resulting in an Aiken's V value of 0.9, which is considered "Valid" according to the standard Aiken's V interpretation, indicating strong agreement among the validators. For information quality, the scores were slightly lower, with V1 scoring 4.75, and V2 and V3 scoring 4.125. The total sum of scores for this aspect was 10, resulting in an Aiken's V value of 0.83, which also falls within the "Valid" range. While this value is slightly lower than usability, it still reflects a high level of validation from the validators.

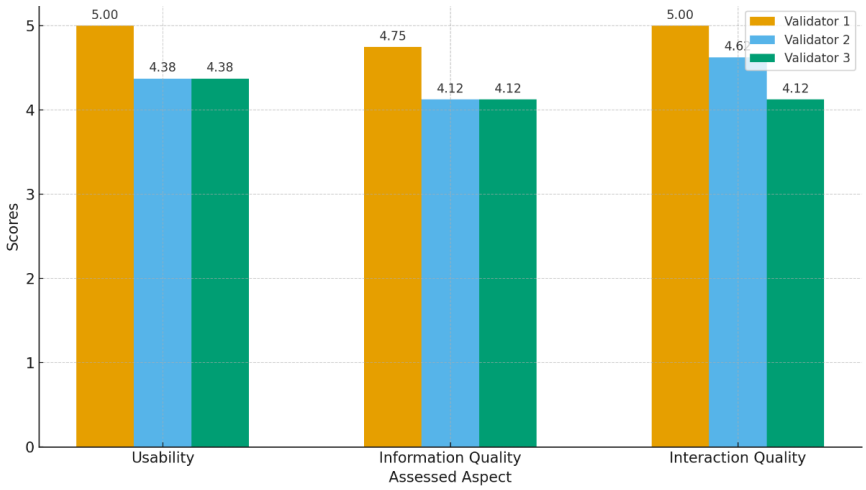


Figure 2. Comparison of scores by validator

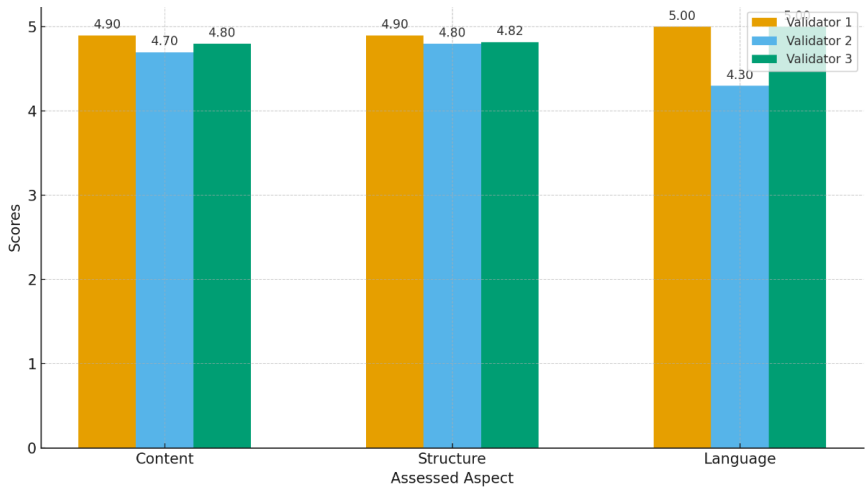
Lastly, as illustrated in Figure 2, the Interaction Quality aspect received high ratings, with V1 providing a perfect score of 5, and V2 and V3 giving scores of 4.625 and 4.125, respectively. The sum of the scores for Interaction Quality was 10.75, leading to another Aiken's V of 0.9, confirming that this aspect is also considered "Valid." This consistency in high ratings suggests that the validators highly regarded the AR media's interaction features. Overall, the AR media's validation for Usability, Information Quality, and Interaction Quality all received Aiken's V values above 0.8, indicating that the media is considered valid and effective for educational use. The Total sum of scores and Aiken's V value of 0.88 further support the conclusion that the developed AR media is of high quality and suitable for implementation in the classroom.

Table 5.
Aiken's V validation for AR-module

Assessed Aspect	Validator			s1	s2	s3	∑s	n(c-1)	Aiken's V	Status
	V1	V2	V3							
Content	4.9	4.7	4.8	3.9	3.7	3.8	11.4	12	0.95	Valid
Structure	4.9	4.8	4.82	3.88	3.76	3.82	11.5	12	0.956	Valid
Language	5	4.3	5	4	3.33	4	11.3	12	0.944	Valid
Total	15	14	14.6	11.8	10.8	11.6	34.2	36	0.95	Valid

Table 5 presents the results of Aiken's V validation for the Augmented Reality (AR) module, focusing on three key aspects: Content, Structure, and Language. The validation was conducted by three validators (V1, V2, and V3), and their ratings, summed scores (∑s), and the calculated Aiken's V value for each aspect are presented. In the Content aspect, the ratings from the three validators were close, with V1 providing a score of 4.9, V2 scoring 4.7, and V3 scoring 4.8. The total sum of the scores for this aspect was 11.4, leading to an Aiken's V value of 0.95. This high value indicates strong agreement among the validators and suggests that the content of the AR module is well-validated and considered adequate for educational purposes. The Content aspect was deemed "Valid," confirming its high quality.

Figure 3.
Aiken's V validation for AR-module



For the Structure aspect, the scores from the validators were similarly high, with V1 scoring 4.9, V2 giving 4.8, and V3 providing 4.82. The total sum of scores for structure was 11.5, yielding an Aiken's V of 0.956, which is even higher than the Content aspect. This indicates an even stronger validation for the structural design of the AR module, ensuring it is well-organized and effective for guiding the learning process. The Structure aspect is also categorized as "Valid." In the Language aspect, the ratings were slightly more varied, with V1 scoring 5, V2 providing 4.3, and V3 giving 5. The sum of the scores for language was 11.3, resulting in an Aiken's V value of 0.944, which is still within the "Valid" range, although slightly lower than Content and Structure. This suggests that while the language used in the AR module is generally effective and transparent, there may be room for minor improvements, particularly based on the slight discrepancy in V2's rating. Overall, the AR module's Content, Structure, and Language aspects all received Aiken's V values above 0.9, indicating that the module is highly valid and suitable for use. The total Aiken's V value of 0.95 further supports the conclusion that the AR module is well-constructed and effective for its educational goals, meeting the criteria for validity across all assessed aspects.

3.4 Implementation results

The results of the practicality test based on teacher and student responses are presented. The practicality test aims to evaluate the effectiveness and usability of the Augmented Reality (AR) media developed for the Earth and Solar System module. The test is based on feedback from both teachers and students, assessing various aspects such as usability, information quality, and interaction quality, where the data is presented in Figure 4.

Figure 4. Practicality test based on teacher and student responses

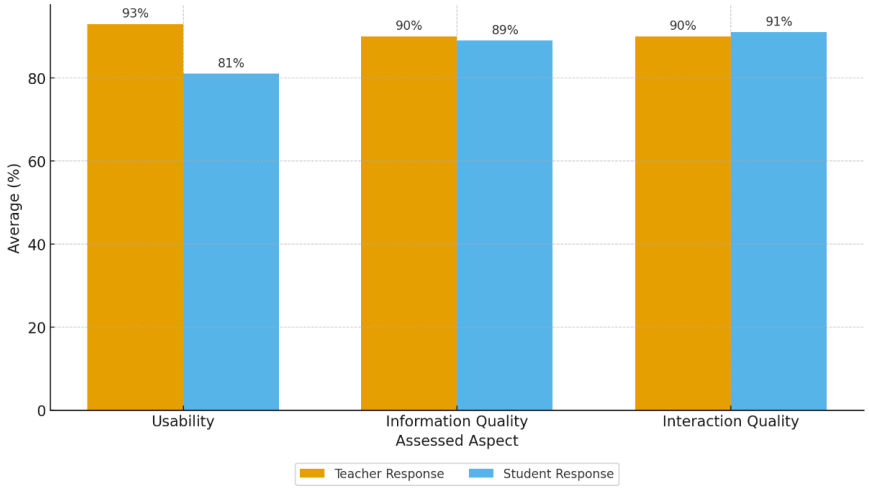


Figure 4 presents the practicality test results conducted with teachers and students, focusing on three main aspects: Usability, Information Quality, and Interaction Quality. Regarding usability, the teachers rated the AR media with an average score of 93%, categorizing it as Very Practical. In contrast, students gave a lower rating of 81%, which still falls under the Practical category, indicating that while the media was effective for most students, some may have found it slightly less user-friendly than the teachers' perception. For Information Quality, teachers and students gave high ratings, with the teachers scoring 90% (Very Practical) and the students scoring 89% (Very Practical). This suggests that the content presented through the AR media was well-received and understood by both groups, confirming the effectiveness of the media in conveying educational material.

Regarding Interaction Quality, the teachers again rated the media highly, scoring 90% (Very Practical), while the students rated it slightly higher at 91% (Very Practical). This shows that both teachers and students found the interactive elements of the AR media engaging and conducive to learning. Finally, the Total scores reflect similar trends, with the teachers providing an average of 91% (Very Practical) and the students 87% (Very Practical). The overall positive ratings from both groups highlight the AR media's strong practicality in terms of usability, information quality, and interaction, suggesting that it is an effective tool for enhancing learning in the classroom. These results demonstrate that the AR media developed for the Earth and Solar System module was practical and well-received, with teachers and students recognizing its value in learning.

3.5 Evaluation results

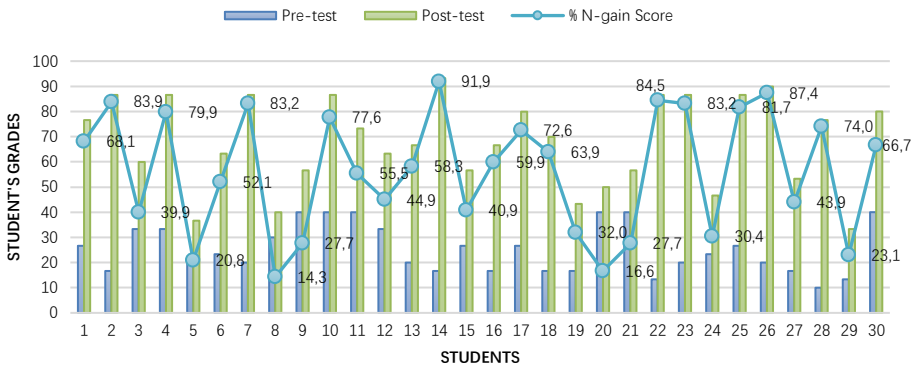
The evaluation results are presented based on the N-gain scores from pre-test and post-test participants. The N-gain score measures the improvement in students' learning outcomes after the intervention, in this case, using Augmented Reality (AR) media for the Earth and Solar System module. Comparing the pre-test and post-test scores provides insights into the effectiveness of the AR media in enhancing students' understanding of the material.

Table 6. Analysis of N-gain scores in pre-test and post-test participants

	N	Min.	Max.	N-gain Score	N-gain (%)	Criteria
Pre-test	30	0.20	0.92	0.562	56.2%	Effective
Post-test	30					

Table 6 shows the N-gain scores for the pre-test and post-test participants. The pre-test results indicate an average N-gain score of 0.562, or 56.2%, which is categorized as Effective. This suggests that students had moderate prior knowledge, and the AR media used in the study effectively improved their understanding of the material. The post-test data, when compared, would likely demonstrate further improvements, confirming the positive impact of the AR media on students' learning outcomes.

Figure 5. Comparison of data trends of N-gain score



The results from the pre-test indicate a solid baseline for students' initial understanding, and the effectiveness of the AR media in improving learning outcomes can be further validated by comparing the post-test results to these baseline scores. The N-gain score of 56.2% indicates that the AR media positively impacted students' learning, enhancing their understanding of the subject matter.

4. Discussion

This study aimed to develop and evaluate Augmented Reality (AR)-based learning media for the Earth and Solar System topics in middle school science education. The findings from the analysis, design, development, and evaluation phases underscore the effectiveness of AR technology in enhancing student engagement, understanding, and overall academic performance. By addressing the limitations of traditional teaching methods, such as static images and videos, which often fail to convey abstract concepts effectively, AR provides an interactive and immersive experience. This approach made complex scientific ideas more accessible and engaging, transforming how students interact with and understand the material.

The results of this study are consistent with findings from previous research that highlight the potential of AR in education. Studies by (Hajirasouli & Banihashemi, 2022; Kamińska et al., 2023; Lampropoulos et al., 2022) emphasized how AR significantly enhances interactive learning by integrating digital content into the real world. This approach makes abstract concepts more tangible for students, which aligns with the results of this study, where AR was particularly effective in explaining complex topics like the Solar System. Additionally, similar to the research by (Drljević et al., 2022; Wen, 2021), which confirmed AR's effectiveness in both classroom and independent learning, this study corroborates the idea that AR can increase student engagement and deepen their understanding. However, this study expands on existing research by focusing on middle school science education in rural areas, such as Pasaman Regency, where access to advanced learning media may be limited.

The results from the practicality test, presented in Table 4, show a high level of acceptance from teachers and students. Teachers rated the AR media highly in terms of usability, information quality, and

interaction quality, with an average score of 91% in usability, categorizing it as Very Practical. In contrast, students gave the media a slightly lower rating, particularly in usability, where their average score was 81% (Practical). This discrepancy suggests that while the AR media was effective for most students, some faced challenges with usability, likely due to varying levels of familiarity with AR technology. Despite this, the overall positive feedback demonstrates that AR has the potential to significantly enhance the learning experience, especially when paired with adequate teacher training and technological support.

Compared to traditional media, such as static images and videos, AR-based learning media offered an interactive and immersive experience, bridging the gap in students' understanding of abstract concepts. Research by (Mansour et al., 2025; Prit Kaur et al., 2022) supports this notion, as AR facilitates better comprehension of complex concepts. This study further confirms these findings by significantly improving students' performance in the Earth and Solar System topics. The N-gain score of 56.2% indicates a positive impact, reinforcing the findings of (Nikimaleki & Rahimi, 2022; Tuta & Luić, 2024), who observed that AR improves student learning outcomes. However, this study also revealed usability challenges for some students, which were less emphasized in prior research. This discrepancy could be due to varying levels of technological familiarity, and it warrants further exploration in future studies. In conclusion, the study confirms that AR has significant potential as an educational tool for enhancing understanding and engagement with complex scientific concepts. The findings align with previous research and offer new insights into the use of AR in rural middle school settings. To fully capitalize on the benefits of AR, continued development, teacher training, and further research are needed to address usability challenges and optimize the integration of AR into classrooms.

5. Limitations and recommendations

While this study demonstrates the effectiveness of Augmented Reality (AR) in enhancing student engagement and understanding, several limitations should be considered. First, the study was conducted in a specific rural setting (SMP Negeri 1 Tigo Nagari, Pasaman Regency), which may limit the generalizability of the findings to other regions, especially urban areas where access to technology may be more widespread. Second, despite the overall positive feedback on AR usability, some students faced challenges with its use. This discrepancy could be attributed to varying levels of familiarity with AR technology and access to the necessary devices, as not all students had access to smartphones or tablets capable of supporting AR applications. Additionally, although the teacher ratings were high, there is still a need for further training and support to ensure effective implementation of AR technology in classrooms.

In terms of recommendations, future research should explore strategies to overcome the usability challenges identified in this study. It is essential to provide adequate training for students and teachers to familiarize them with AR technology. Additionally, schools in rural areas should be provided with the necessary resources and support, such as access to devices and reliable internet, to ensure the successful implementation of AR in classrooms. Further studies could also consider expanding the sample size and incorporating a diverse range of educational contexts to assess the generalizability of the findings across different settings. Lastly, while the study focused on middle school students, there is potential to extend the use of AR media to other educational levels. Research could explore how AR-based media can be adapted for higher education or used in different subjects beyond the Earth and Solar System, providing insights into the broader applications of AR in education.

6. Conclusion

This study confirms that Augmented Reality (AR) is a highly effective tool for enhancing student understanding and engagement in complex scientific concepts. The development and implementation of AR-based learning media for teaching the Earth and Solar System significantly improved students' academic performance, particularly in grasping abstract ideas that traditional media like pictures and videos struggled to convey. The positive feedback from both teachers and students highlights the practical

potential of AR in middle school science classrooms, especially in rural areas where access to advanced learning technologies is limited. However, the study also revealed some challenges related to the usability of the AR media, particularly among students with varying levels of familiarity with AR technology. These challenges underscore the need for additional teacher training and technological support to optimize the integration of AR in educational settings. Future research should focus on addressing these usability issues, expanding the scope to other educational levels, and exploring the broader applications of AR across various subjects to capitalize on its potential in education fully.

Author's Declaration

Author contribution

Rozalina: Conceptualization, methodology, Validation, data curation, and writing-original draft. **Faiza Rini**: Investigation, resources, writing-review & editing data curation. **Felia Siska**: Investigation, resources, writing-review & editing data curation.

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Conflict of interest

There are no conflicts of interest in this research.

Ethical clearance

The study protocol was reviewed and approved by Government of Pasaman Regency, approval number 800/106/SMP/1/2025. All procedures were performed in accordance with the ethical standards of the Declaration of Helsinki. Written informed consent was obtained from all student and teacher participants prior to data collection.

Data availability

The data that support this study's findings are available from the corresponding author upon reasonable request.

AI Statement

This article's grammar was improved with assistance from ChatGPT. The author confirmed that all revisions align with the topic and research data, and an English-language specialist validated both the data and wording. The manuscript contains no AI-generated sentences.

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