

Effectiveness of Augmented Reality in Enhancing Critical Thinking in Physics Learning: A Meta-Analysis

Martin Albertus Silitonga^{1*}, Emiliannur²

¹ Physics Education Study Program, Universitas Negeri Padang, Padang, Indonesia

² Department of Physics, Universitas Negeri Padang, Padang, Indonesia

ARTICLE INFORMATION

Received : 2026-03-30
Revised : 2026-03-31
Accepted : 2026-03-31

Correspondence

Email : malbertus35@gmail.com
Phone :

KEYWORDS :

Augmented Reality;
Meta-Analysis; Critical
Thinking; Physics
Learning; Effect Size

ABSTRACT

This study addresses the persistent challenge of students' difficulty in understanding abstract physics concepts, which often leads to low critical thinking skills. This issue highlights the need for innovative learning approaches that can support meaningful and interactive learning experiences. Augmented Reality (AR) has emerged as a promising solution by providing real-time visualization and interactive learning environments that help students better understand complex concepts. This study aims to examine the effectiveness of AR in enhancing students' critical thinking skills in physics learning. A meta-analysis approach was employed by analyzing 24 relevant studies that met the inclusion criteria. Data were analyzed by calculating effect size using Microsoft Excel and JASP, and the results were visualized using a forest plot. In addition, moderator analyses were conducted based on education level and learning materials. The findings reveal that AR has a high level of effectiveness, with an overall effect size of 0.765, indicating a strong positive impact on students' critical thinking skills. Therefore, AR can be considered an effective and innovative learning medium to support physics education.



This is an open access article distributed under the Creative Commons 4.0 Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. ©2023 by author and Universitas Negeri Padang.

INTRODUCTION

The rapid development of information and communication technology has significantly transformed educational practices, including physics learning (Zhu et al., 2020; Yoon et al., 2020). Physics is often perceived as a difficult subject due to its abstract concepts, such as forces, electric fields, and electromagnetic waves, which are not directly observable (Samsudin & Widodo, 2021). This condition makes it challenging for students to construct meaningful understanding, particularly in developing higher-order thinking skills such as critical thinking (Putri & Surjono, 2021). In practice, conventional teaching approaches are still dominant and tend to emphasize theoretical explanations with limited interactive support, resulting in less engaging and less effective learning experiences (Fitria et al., 2020; Rahmawati & Suparmi, 2021).

Physics learning is often constrained by the abstract nature of its concepts, which makes it difficult for students to develop critical thinking skills. To address this issue,

innovative learning approaches are required to support more meaningful and interactive learning experiences. Augmented Reality (AR) offers a potential solution by integrating virtual objects into real-world environments, enabling students to visualize abstract phenomena more concretely (Yoon et al., 2020; Chang et al., 2022). From a theoretical perspective, AR supports constructivist learning principles, where students actively construct knowledge through interaction and exploration, which is essential for developing higher-order thinking skills such as critical thinking (Fidan & Tuncel, 2019; Suhendra et al., 2022).

Augmented Reality (AR) has emerged as a promising technological innovation to address these challenges. AR integrates virtual elements into real-world environments in real time, enabling students to visualize abstract concepts in a more concrete and interactive way (Yoon et al., 2020; Kurniawan et al., 2020). Several studies have demonstrated that AR can enhance students' motivation, engagement, and conceptual understanding in science learning (Fidan & Tuncel, 2019; Suhendra et al., 2022). In physics education, AR facilitates three-dimensional visualization and interactive simulations, which are essential in supporting critical thinking and problem-solving skills (Chang et al., 2022; Dewi & Prasetya, 2023).

Despite these advantages, findings regarding the effectiveness of AR in physics learning remain inconsistent. Some studies report significant improvements in learning outcomes and critical thinking skills (Socrates & Mufit, 2023), while others show limited or non-significant effects depending on the context of implementation (Setiawan et al., 2021; Rahmawati & Suparmi, 2021). These variations may be influenced by several factors, including differences in educational levels, learning materials, duration of intervention, and technological readiness (Vidak et al., 2023; Chang et al., 2022). Therefore, it is difficult to establish a generalized conclusion regarding the effectiveness of AR in physics learning.

Furthermore, most existing studies are conducted as individual experimental research and do not provide comprehensive evidence across multiple contexts. Although several review studies have explored the use of AR in education, they tend to rely on descriptive approaches without synthesizing quantitative findings (Ali et al., 2023; Islamianti et al., 2023). As a result, there is still a lack of empirical evidence that integrates effect size across studies to determine the overall effectiveness of AR in physics learning. Meta-analysis offers a systematic and quantitative approach to combine results from multiple studies, allowing for more robust and objective conclusions (Retnawati et al., 2018; Fitria et al., 2020).

Based on these gaps, this study aims to examine the effectiveness of Augmented Reality in enhancing students' critical thinking skills in physics learning through a meta-analysis approach. In addition, this study investigates the influence of moderator variables, namely educational level and learning materials, on the effectiveness of AR. The findings are expected to contribute to the development of technology-based physics learning and provide evidence-based recommendations for educators and policymakers in implementing AR effectively (Chang et al., 2022; Vidak et al., 2023).

METHODS

Research Design

This study employed a quantitative approach using meta-analysis to synthesize findings from multiple primary studies on the effectiveness of Augmented Reality (AR) in physics learning. Meta-analysis was chosen because it enables the integration of statistical

results across studies and provides a more robust estimation of effect size compared to individual studies (Retnawati et al., 2018; Fitria et al., 2020).

Data Sources and Search Strategy

Relevant studies were identified through systematic searches in electronic databases, including Google Scholar, Sinta, and Scopus. The search was conducted using combinations of keywords such as “Augmented Reality”, “physics learning”, “critical thinking”, and “effect size”. The identification and selection process followed the PRISMA guidelines to ensure transparency and reproducibility in study selection (Moher et al., 2009).

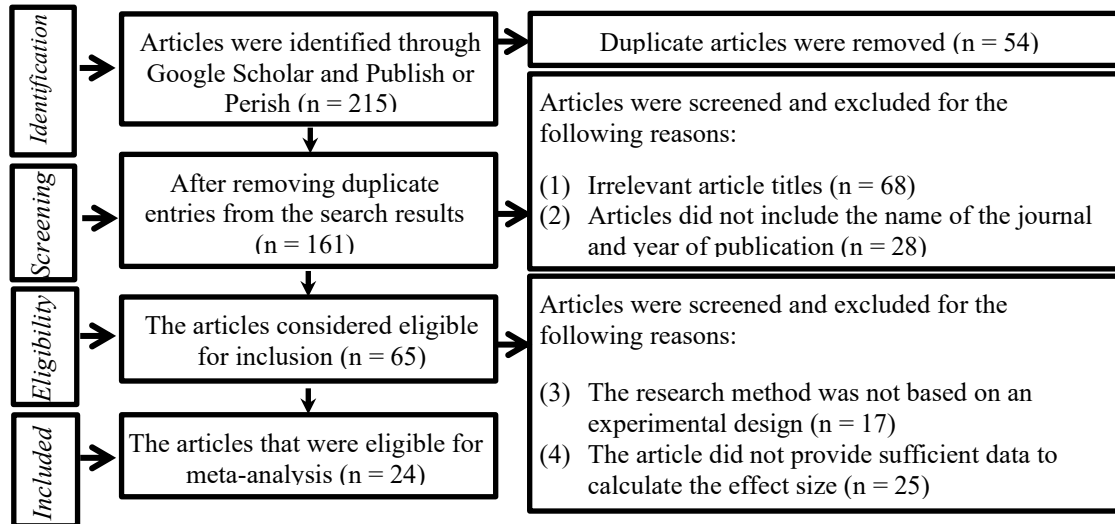


Figure 1. PRISMA Flow Diagram

Inclusion and Exclusion Criteria

The inclusion criteria were defined as follows: (1) quantitative studies employing experimental or quasi-experimental designs, (2) studies investigating the use of AR in physics learning, (3) studies published between 2020 and 2025, (4) studies providing sufficient statistical data to calculate effect size (e.g., mean, standard deviation, t-value, or p-value), and (5) full-text articles available. Studies that did not meet these criteria or lacked sufficient data were excluded from the analysis. Based on this process, a total of 24 studies were included in the meta-analysis.

Data Analysis

The effect size was calculated using the standardized mean difference (SMD) approach. The analysis was performed using Microsoft Excel and JASP software. The interpretation of effect size followed Cohen’s criteria, where 0.2 indicates a small effect, 0.5 a medium effect, and 0.8 a large effect (Cohen, 1988). The results were presented using forest plots to visualize the distribution and consistency of effect sizes across studies.

Table 1. The Interpretation of Effect Size

<i>Value</i>	<i>Interpretation</i>
$0,20 \leq d < 0,50$	<i>Small Effect Size</i>
$0,50 \leq d < 0,80$	<i>Medium Effect Size</i>
$d \geq 0,8$	<i>Large Effect Size</i>

(Cohen’s J., 1998)

Effect Size Formula Data Coding

To examine potential sources of variation, moderator analysis was conducted based on educational level and learning materials. This analysis aimed to identify conditions under which AR is more effective in enhancing students' critical thinking skills in physics learning (Chang et al., 2022; Vidak et al., 2023). When a study used a single group (pre-test and post-test without a control group), the effect size was calculated using:

$$d = \frac{M_{post} - M_{pre}}{SD_{pre-post}} \quad (1)$$

Where:

M_{pre}, M_{post} = Pre-test and post-test mean

SD_{pre}, SD_{post} = Pre-test and post-test standard deviation

Or if only paired t and N were reported:

$$d = \frac{t}{\sqrt{N}} \quad (2)$$

Calculate the effect size so that the data distribution is normal and has a stable variance before averaging using the following equation :

$$z = Y_i = 0,5 \times \ln \frac{1+r}{1-r} \quad (3)$$

Where:

$d = z = Y_i = \text{Cohen's } d$

r = magnitude of the correlation value r

To calculate the t-statistic value to obtain the correlation value r , use the following equation:

$$r = \frac{t}{\sqrt{t^2 + N - 2}} \quad (4)$$

Where:

t : the magnitude of the t-test statistic value

N : the number of data samples

After calculating the effect size, the standard error (SE) of g was computed with the following formula:

$$SE = \sqrt{\frac{1}{N-3}} \quad (5)$$

This standard error is essential for further meta-analysis steps like confidence intervals and publication bias analysis. The interpretation of effect size values in this study referred to Cohen's classification (2007), which categorizes the strength of an intervention based on its numerical value.

RESULTS AND DISCUSSION

Results

The results of this meta-analysis are presented based on the overall effect size, as well as subgroup analyses based on learning materials and educational levels.

Overall Effect Size

The overall effect size of Augmented Reality (AR) in enhancing students’ critical thinking skills in physics learning was found to be **0.765**. According to Cohen’s criteria, this value falls into the **high category**, indicating that AR has a strong positive effect on students’ critical thinking skills.

Table 2. Summary of Meta-Analysis Results

Parameter	Value
Number of Studies	24
Effect Size	0.765
Interpretation	High

The results presented in Table 2 indicate that Augmented Reality (AR) has a high level of effectiveness in enhancing students’ critical thinking skills in physics learning. This finding suggests that AR is capable of facilitating deeper cognitive engagement by allowing students to interact with abstract concepts in a more concrete and meaningful way. The high effect size also reflects that AR can support the development of higher-order thinking skills, particularly in analyzing and evaluating scientific phenomena. This result implies that the integration of AR into physics learning can significantly improve the quality of learning outcomes. Therefore, AR can be considered a highly effective instructional medium in supporting students’ critical thinking skills.

Effect Size Based on Learning Materials

The analysis based on learning materials shows that the effectiveness of AR varies across different physics topics. In general, AR tends to provide higher effect sizes in topics that involve abstract and complex concepts, such as electromagnetic phenomena and wave-related materials. This indicates that AR is particularly effective in supporting visualization-intensive topics, where students require concrete representations to understand abstract concepts.

Table 3. Effect Size Based on Learning Material

Learning Material	Number of Studies	Effect Size	Interpretation
Solar system	4	0.93	High
Mechanics	9	1.03	High
Applied Physics of Matter and Fluids	4	0.53	Medium
Electricity	2	0,57	Medium
Earth and environmental physics	3	0,41	Small
Optics and Light	2	0,43	Small

The results in Table 3 show that the effectiveness of Augmented Reality (AR) varies across different physics learning materials. AR demonstrates the highest effectiveness in topics such as mechanics and the solar system, which strongly rely on visualization and spatial representation. In contrast, its effectiveness is moderate in topics such as fluids and electricity, and relatively low in optics and earth-related topics. This variation indicates that AR is more effective when applied to learning materials that require strong visual and conceptual representation. The findings suggest that the suitability between the

characteristics of the learning material and the features of AR plays an important role in determining its effectiveness.

Effect Size Based on Educational Level

The subgroup analysis based on educational level reveals variations in the effectiveness of AR across different levels of education. The results indicate that AR tends to be more effective at the senior high school level compared to other levels. This may be due to students' cognitive readiness and their ability to engage with interactive digital media, which are more developed at this stage.

Table 4. Effect Size Based on Education Level

Educational Level	Number of Studies	Effect Size	Interpretation
Elementary school	5	0,92	High
Junior High School	5	0.67	Medium
Senior High School	10	0.83	High
University	4	0.51	Medium

The results in Table 4 indicate that the effectiveness of Augmented Reality (AR) varies across different educational levels. AR shows high effectiveness at the elementary and senior high school levels, while its effectiveness is moderate at the junior high school and university levels. This pattern suggests that students' cognitive readiness and learning characteristics play an important role in determining the effectiveness of AR. At the senior high school level, students are generally more capable of engaging with abstract concepts and interactive digital media, which enhances the impact of AR. Meanwhile, at other levels, differences in learning readiness and adaptation to technology may influence the effectiveness of AR in supporting critical thinking skills.

Distribution of Effect Size Data in JASP Software

The distribution of effect sizes across studies is shown in Figure 1, highlighting the variation and overall trend of the effectiveness of Augmented Reality in physics learning.

Model Summary

Table 5. Distribution of Effect Size Data Based om JASP Software

<i>Meta-Analytic Tests</i>		
	Test	p
Heterogeneity	$Q_c(23) = 320.21$	< .001
Pooled effect	$t(23) = 16.08$	< .001

<i>Meta-Analytic Estimates</i>						
			95% CI		95% PI	
	Estimate	Standard Error	Lower	Upper	Lower	Upper
Pooled effect	0.495	0.031	0.431	0.558	0.431	0.558

Note. 1 observations were omitted due to missing values.

Based on the processed eta analysis data in the table, the distribution of effect size data can be seen in the following forest plot.

Forest Plot

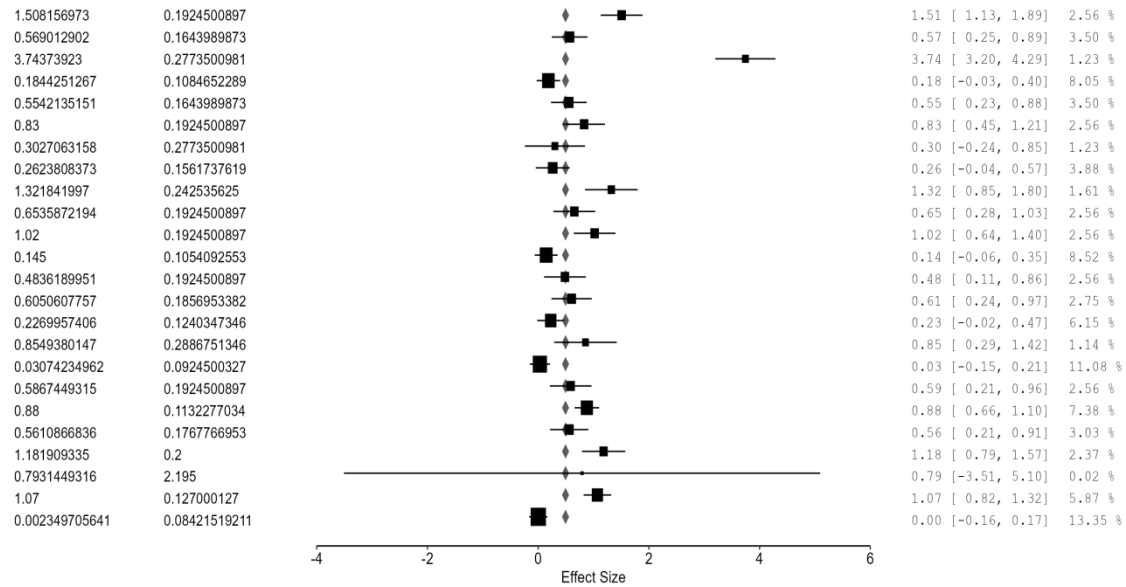


Figure 2. Forest Plot of Effect Size Data

The forest plot presented in Figure 2 illustrates the distribution of effect sizes across the included studies. The majority of studies show positive effect sizes, indicating that Augmented Reality (AR) generally has a beneficial impact on students’ critical thinking skills in physics learning. However, the distribution also reveals variations in the magnitude of the effect sizes, with some studies showing moderate to lower effects. This variation suggests that the effectiveness of AR is not uniform across all studies and may be influenced by differences in implementation, learning context, and student characteristics. Overall, the forest plot confirms a consistent positive trend, while also highlighting the presence of variability among the included studies.

Discussion

The findings of this study demonstrate that Augmented Reality (AR) has a strong positive impact on students’ critical thinking skills in physics learning, as reflected by the high overall effect size (0.765). This result indicates that AR is not merely a supplementary tool but a powerful instructional medium that enhances higher-order thinking by enabling students to visualize and interact with abstract scientific concepts. This finding is consistent with previous studies showing that AR significantly improves conceptual understanding and promotes active engagement in science learning (Chang et al., 2022; Yilmaz & Batdi, 2020).

The effectiveness of AR can be explained by its ability to provide immersive and interactive representations of abstract physics phenomena. Physics concepts often require spatial and dynamic visualization, which are difficult to achieve through conventional instruction. AR bridges this gap by integrating virtual elements into real-world contexts, allowing students to construct knowledge through direct interaction and exploration. This

aligns with constructivist learning theory, which emphasizes active learning as a foundation for developing critical thinking skills (Fidan & Tuncel, 2019; Suhendra et al., 2022).

However, a more detailed analysis reveals that the effectiveness of AR varies across different learning materials. AR shows high effectiveness in topics such as mechanics and the solar system, which strongly rely on visualization and spatial representation. In contrast, its effectiveness decreases to a medium level in topics such as fluids and electricity, and becomes relatively low in optics and earth-related topics. This variation suggests that the success of AR is closely related to the nature of the learning content. Previous studies have also emphasized that AR is particularly effective for abstract and complex scientific concepts that require visual representation (Dewi & Prasetya, 2023; Chang et al., 2022). Therefore, the alignment between instructional media and content characteristics is a critical factor in optimizing learning outcomes.

In addition to learning materials, differences in effectiveness are also observed across educational levels. The findings indicate that AR is most effective at the senior high school level, compared to junior high school and university levels. This may be explained by differences in cognitive development and technological readiness among students. Senior high school students generally possess higher levels of abstract thinking and are more capable of engaging with interactive digital learning environments. Similar findings have been reported in previous studies, which highlight that the effectiveness of technology-enhanced learning is influenced by students' readiness and learning context (Socrates & Mufit, 2023; Vidak et al., 2023).

Furthermore, the distribution of effect sizes presented in the forest plot reveals noticeable variability across studies, including several anomalous findings. While most studies report positive effects, some show lower or non-significant impacts. These inconsistencies may be attributed to differences in instructional design, duration of implementation, technological accessibility, and the level of familiarity with AR-based learning environments (Setiawan et al., 2021; Vidak et al., 2023). This finding reinforces the idea that the effectiveness of AR is not universally consistent but depends heavily on contextual and pedagogical factors.

Importantly, these variations represent a key contribution of this study. While previous research has reported inconsistent findings, this meta-analysis provides a more comprehensive understanding by integrating and explaining these differences. The results suggest that AR effectiveness is conditional rather than absolute, emphasizing that technology alone is insufficient without appropriate instructional design. This perspective supports previous studies that highlight the importance of pedagogical integration in technology-based learning (Chang et al., 2022; Fidan & Tuncel, 2019).

Despite its strong effectiveness, this study has several limitations. The variation in effect sizes indicates differences in research conditions that may influence the results. In addition, the analysis was limited to studies with complete statistical data, which may exclude relevant studies with incomplete reporting. Therefore, future research is recommended to explore additional factors such as the quality of AR applications, instructional strategies, and duration of implementation to better understand how AR can be optimally applied in physics learning.

CONCLUSION

This study shows that Augmented Reality (AR) is an effective learning medium for improving students' critical thinking skills in physics learning. AR helps students understand abstract concepts more clearly through interactive and visual learning experiences. The findings also indicate that AR is more effective when applied to topics that require strong visualization, such as mechanics and astronomy-related concepts. In addition, AR demonstrates greater effectiveness at the senior high school level, where students have higher readiness to engage with interactive learning environments. However, its effectiveness is not uniform across all learning contexts and depends on the characteristics of the learning material and students. These results highlight that the success of AR is not determined solely by the technology itself, but by how it is implemented in the learning process. Therefore, careful instructional design is essential to ensure that AR can be used optimally to support students' critical thinking skills.

REFERENCES

- Ali, A., Putri, D., & Kuswanto, H. (2023). Augmented Reality in Physics Education: A Systematic Review. *Journal of Science Education*, 15(2), 120–135.
- Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences (2nd ed.)*. Lawrence Erlbaum Associates.
- Chang, C. Y., Hsu, Y. S., & Wu, H. K. (2022). Effects of Augmented Reality on Students' Learning Outcomes in Science Education: A Meta-Analysis. *Educational Research Review*, 35, 100437.
- Dewi, P. S., & Kuswanto, H. (2023). The Effectiveness of the Use of Augmented Reality-Assisted Physics E-Module Based on Pedicab to Improve Mathematical Communication and Critical Thinking Abilities. *Journal of Technology and Science Education*, 13(1), 53-64.
- Dewi, R., & Prasetya, A. (2023). The Effectiveness of Augmented Reality in Physics Virtual Experiments. *Jurnal Pendidikan Fisika Indonesia*, 19(1), 45–53.
- Fidan, M., & Tuncel, M. (2019). Integrating Augmented Reality into Problem-Based Learning: The Effects on Learning Achievement and Attitude. *Computers & Education*, 142, 103635.
- Fitria, Y., Sari, M., & Nurdin, E. (2020). Meta-Analysis of Learning Media in Science Education. *Jurnal Pendidikan Sains*, 8(2), 101–110.
- Ghifari, Y., Rienovita, E., & Amelia, D. (2025). Penggunaan Augmented Reality untuk Meningkatkan Kemampuan Berpikir Kritis dalam Pelajaran IPA. *Jurnal Education and Development*, 13(1), 28-36.
- Hasan, I., Arafah, K., & Hasyim, M. (2025). The Impact of Augmented Reality Media on High School Students' Critical Thinking Skills in Physics. *Jurnal Pendidikan Fisika*, 13(3), 600-613.
- Herliandry, L. D., Kuswanto, H., & Hidayatulloh, W. (2021). Improve Critical Thinking Ability through Augmented Reality Assisted Worksheets. *Advances in Social Science, Education and Humanities Research*, 541, *Proceedings of the 6th International Seminar on Science Education (ISSE 2020)*, 611–617. Atlantis Press.
- Islamianti, R., et al. (2023). Bibliometric Analysis of Augmented Reality in Science Learning. *International Journal of Instruction*, 16(1), 233–250.
- Kurnianto, F., Rahmat, A. D., & Kuswanto, H. (2024). The Effect of Augmented Reality

- Integrated Traditional Games Nglarak Blarak to Improve Critical Thinking and Graphical Representation Skills. *Pegem Journal of Education and Instruction*, 14(2), 340-346.
- Pertiwi, F. N., Kitthawee, U., Ramadhan, N. H., & Muna, I. A. (2025). Phys'AR as a Learning Innovation: Strengthening Critical Thinking and Argumentation Skills in Applied Physics. *Jurnal Pendidikan Fisika*, 13(3), 461-478.
- Putri, R., & Surjono, H. D. (2021). The Impact of Digital Learning Media on Students' Critical Thinking Skills. *Journal of Physics Education*, 9(2), 88-96.
- Rahmayani, F., Kuswanto, H., & Rahmat, A. D. (2024). Development of E-Book Integrated Augmented Reality Based on STEM Approaches to Improve Critical Thinking and Multiple Representation Skills in Learning Physics. *International Journal of Information and Education Technology (IJJET)*, 14(4), 632-641.
- Rahmawati, D., & Suparmi, S. (2021). Augmented Reality in Physics Learning: Effects on Conceptual Understanding. *Jurnal Pendidikan Fisika*, 10(1), 25-32.
- Retnawati, H., Apino, E., Kartianom, K., Djidu, H., & Anazifa, R. D. (2018). *Pengantar Analisis Meta*. Yogyakarta: Parama Publishing.
- Saputri, A. A., Mohtar, L. E., Arsini, Fitra, I. S., & Prasetyo, I. S. (2024). Critical Thinking Skills (CTS) Through Augmented Reality Worksheets Using the Inquiry-Scaffolding Models. *Physics Education Research Journal*, 6(1), 21-28.
- Sebastian, R., & Kuswanto, H. (2025). The Effectiveness of A Physics E-Book on Rotational Dynamics of A Traditional Top Game Assisted by Augmented Reality to Improve Students' Critical Thinking Skills And Visual Representations. *Revista Mexicana de Física E*, 22(020205), 1-12.
- Setiawan, A., et al. (2021). The Implementation of Augmented Reality in Science Learning: A Quasi-Experimental Study. *Jurnal Pendidikan IPA Indonesia*, 10(3), 345-352.
- Socrates, M., & Mufit, F. (2023). The Use of Augmented Reality in Physics Learning to Improve Students' Motivation and Understanding. *Jurnal Penelitian Pembelajaran Fisika*, 9(1), 12-20.
- Suhendra, A., et al. (2022). Augmented Reality in Physics Learning: Improving Students' Learning Outcomes. *Jurnal Pendidikan Sains Indonesia*, 10(2), 200-210.
- Thoha, A., Prasetya, F., Yufrizal, & Rifelino. (2024). Media Pembelajaran Augmented Reality dalam Meningkatkan Berpikir Kritis dan Kreativitas Siswa Negeri 1 Sumatera Barat. *El-Hadhary: Jurnal Penelitian Pendidikan Multidisiplin*, 2(1), 1-10.
- Vidak, A., et al. (2023). Augmented Reality in Education: A Comprehensive Review of Recent Studies. *Computers & Education: Artificial Intelligence*, 4, 100123.
- Yilmaz, R. M., & Batdi, V. (2020). A Meta-Analysis of The Effectiveness of Augmented Reality in Education. *Education and Information Technologies*, 25, 4489-4515.
- Yoon, S., Anderson, E., Lin, J., & Elinich, K. (2020). How Augmented Reality Enables Conceptual Understanding in Science Learning. *Educational Technology & Society*, 23(1), 156-168.
- Zhu, E., Hadadgar, A., Masiello, I., & Zary, N. (2020). Augmented Reality in Healthcare Education: an Integrative Review. *PeerJ*, 8, e10145.