

## AUGMENTED REALITY AS AN INTERACTIVE LEARNING MEDIA ON LIGHT WAVE MATERIAL: A LITERATURE REVIEW

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### Article Info

Received: 26 September 2025

Accepted: 08 December 2025

Publication: 19 December 2025

### Abstract :

This study aims to analyze the effectiveness of Augmented Reality (AR) as an interactive learning medium for understanding light wave concepts in physics. Using a systematic literature review of national and international studies published between 2019 and 2025, this research synthesizes evidence on AR's role in improving students' conceptual understanding and critical thinking. Unlike previous reviews that focused on general AR applications in science education, this study examines explicitly its pedagogical impact on the light wave topic, which remains underexplored despite its abstract and complex nature. The review reveals that AR enhances visualization of light phenomena, fosters active and engaging learning environments, and supports 21st-century skills such as creativity, collaboration, and problem-solving. However, its implementation still faces challenges related to infrastructure, teacher readiness, and content development. Overall, this study provides a novel synthesis that highlights AR's distinctive potential to bridge the gap between abstract theory and concrete experience in learning physics, offering new insights for educators and researchers on topic-specific AR integration.

Keywords: Augmented Reality, Innovation Technology, Learning Media, Light Waves, Physics Education

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## INTRODUCTION

The rapid advancement of digital technology has transformed learning processes across disciplines, including physics education. Among these innovations, Augmented Reality (AR) has emerged as a promising tool that blends virtual objects with real environments, enabling learners to visualize abstract scientific phenomena interactively. Previous studies have demonstrated that AR supports conceptual understanding, engagement, and critical thinking in physics learning (Mashami et al., 2021; Socrates & Mufit, 2022). However, most of these works focus broadly on general topics such as mechanics, optics, or chemistry, without specifically addressing light-wave phenomena, which involve abstract and often misunderstood concepts such as reflection, refraction, interference, and diffraction (Subhashini et al., 2020). That is because AR enables active visualization of reality (Guntara et al., 2023). In addition, students are likely to comprehend the content and convey ideas much better through interactive visualization (Ashari, 2023).

The use of this technology facilitates learning through 3D visualization, animation, and other forms of interactivity, thereby simplifying the explanation of phenomena that are difficult to grasp from direct experience (Juwita et al., 2021). During the pandemic, in the context of distance teaching, AR offers a compelling alternative learning medium, but it has limitations, such as sensitivity to view changes and significant memory consumption (Ashari, 2023). In addition, the use of AR creates a contextual learning experience in which students not only observe but also manipulate and explore objects directly (Yang et al., 2020).

In addition to enhancing conceptual understanding, AR also improves students' critical thinking skills (CTS) (Ardiyanti & Nuroso, 2021). The interactive features of AR make it easier to analyze problems and solve complex concepts, which encourages students to be more engaged in their education (Ashari, 2023). However, the development of this technology so far has led to several problems, including object instability when the camera is stationary and device degradation that degrades AR quality (Vidak et al., 2024). Therefore, further research is needed to develop AR-based learning materials that are more reliable, effective, and can be implemented in physics education (Al-Ansi et al., 2023).

Critical thinking skills (CTS) are among the most important aspects of 21st-century education, especially in science-related fields such as physics (Ashari, 2023). Students at SMAN 11 Makassar have reported difficulties with critical thinking skills due to the lack of application of activities that stimulate thinking and a deficiency of rigorous learning activities during COVID-19 (Asniar et al., 2022). Exacerbating this situation is the learner's apathy, coupled with declining motivation and interest toward learning. Therefore, there is an urgent need to develop more effective teaching strategies that enhance critical thinking skills of the learners, including the application of augmented reality technology (AR) (Mashami et al., 2021). The lack of implementation of learning approaches that require analysis and evaluation has resulted in students not being accustomed to critical thinking (Marudut et al., 2020). Marked overlays, device requirements, technological efficiency, and stability issues pose some challenges in implementing AR (Lai & Cheong, 2022).

Some research has supported the claim that the use of AR learning materials enhances students' understanding of concepts and critical thinking skills (Kalsum et al., 2023). For instance, AR integration into the chemistry curriculum not only enhanced students' understanding of chemical bonds but also received favorable feedback from students (Pauziah & Laksanawati, 2023). Furthermore, another study found that the application of AR techniques at the primary schooling level substantially enhances both digital literacy and critical thinking skills compared with conventional approaches (Fajari & Meilisa, 2022). This demonstrates that there is considerable scope for utilizing AR technology in education to make learning more constructive, active, and enjoyable.

This gap reveals the need for a comprehensive synthesis of research specifically on AR applications for light-wave learning, given the unique visual-spatial challenges this topic presents. Furthermore, existing reviews tend to describe AR's advantages descriptively rather than critically analyzing its pedagogical implications, implementation barriers, and potential future directions. Therefore, this study offers a systematic literature review that not only maps AR-based physics learning research from 2019 to 2025 but also identifies patterns of effectiveness, technological limitations, and areas for pedagogical innovation.

By narrowing its scope to light-wave materials and integrating findings from both national and international studies, this review contributes to the literature by providing a focused, critical, and contextualized understanding of how AR can enhance conceptual and critical thinking skills in physics education. The outcomes are expected to guide educators, developers, and policymakers in integrating AR technology more effectively into physics curricula.

To address this gap, the present study provides a focused and critical synthesis of Augmented Reality (AR) applications in light wave learning, a topic that remains underexplored despite its high conceptual complexity. This research is urgent because misconceptions about light phenomena persist among students, and conventional instructional media often fail to make wave interactions visually and conceptually accessible. The novelty of this systematic review lies in its integration of findings from both national and international studies to construct a comprehensive pedagogical framework that connects AR's interactive affordances with physics learning outcomes. By doing so, this study not only

fills the theoretical and empirical void in the current literature but also offers new insights for designing effective, technology-enhanced learning strategies in physics education.

## RESEARCH METHOD

### *Research Design*

This study uses a qualitative description approach, with a systematic literature review that reviews literature published between 2019 and 2025 and identifies 150 articles. It covers various types of studies, both quantitative and qualitative, examining research that describes the use of augmented reality (AR) as an interactive learning tool in teaching materials (AlGerafi et al., 2023). The literature review was conducted by collecting, analyzing, and interpreting relevant research findings to investigate the effectiveness, limitations, and potential of AR as a physics education tool, particularly for light waves. The data used in this study were obtained from foreign and national journals in databases such as Publish or Perish, ScienceDirect, ArXiv, and Google Scholar for the use of AR in science education (Vidak et al., 2024).

### *Research Target/Subject*

The target of this research is articles or journals relevant to Physics learning using Augmented Reality that review publications from 2019 to 2025. Literature sources were obtained from various national and international databases, such as Publish or Perish, ScienceDirect, ArXiv, and Google Scholar. The subject focus of the research examined in the literature is junior high and high school students studying light-wave phenomena (reflection, refraction, diffraction, etc.). Therefore, this research is not limited to a specific location, but covers relevant Indonesian and international contexts.

### *Research Procedure*

There are certain specific things to keep in mind while performing the literature review, such as studies that are published between the years 2019 and 2025 so that they are considered recent, studies specifically referencing the use of AR in education in general, but especially in physics education, and studies specifically referencing the efficacy of AR in increased understanding, critical thinking ability, and interactive learning (Socrates & Mufit, 2022).

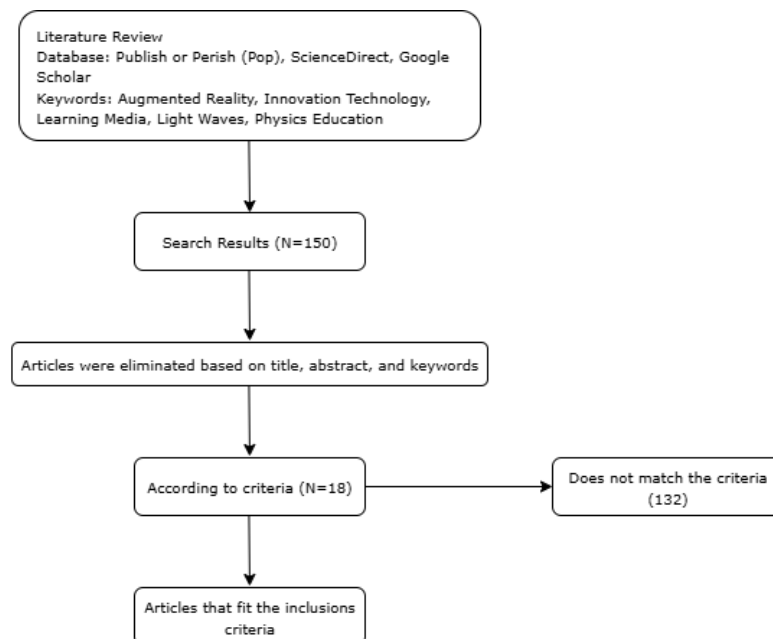


Figure 1. Flowchart of the article inclusion process in the systematic literature phase

### ***Instruments and Data Collection Techniques***

The instruments used were the inclusion criteria (journal type, year of publication, research setting, research subject, and scope of material). Data were collected through scientific databases (Publish or Perish, ScienceDirect, ArXiv, Google Scholar). The data collection technique was document analysis of selected articles.

Table 1. The inclusion criteria

| Category                 | Inclusion criteria   |
|--------------------------|--|
| Journal specifications   | National peer-reviewed journal accredited with a minimum grade 4 (Sinta 4) or international peer-reviewed journals |
| Publication year         | 2019–2025  |
| Research setting         | Indonesia or internationally relevant contexts   |
| Researcher's nationality | Indonesian, or a combination of Indonesian and foreign researchers   |
| Independent variable     | Augmented Reality as an interactive learning medium  |
| Type of study            | Empirical and theoretical  |
| Research subject         | Students at the junior high school and senior high school levels   |
| Material scope           | Focused on Light Wave material (e.g., reflection, refraction, diffraction, etc.)                                   |

### ***Exclusion Criteria***

To ensure the transparency and rigor of the review process, exclusion criteria were applied to exclude studies that did not align with the research focus. Articles were excluded if they:

1. Were published outside the 2019–2025 range;
2. Did not focus on AR in physics or science learning (e.g., AR in medicine, arts, or engineering);
3. Discussed AR conceptually without empirical data or implementation results;
4. Focused on levels outside of junior or senior high school (e.g., university or early childhood education);
5. Were not written in English or Indonesian;
6. Were inaccessible in full-text form or lacked sufficient methodological detail for analysis.

These exclusion criteria helped narrow down the selection to studies most relevant to the research objectives and ensured that the analysis was based on high-quality, comparable data sources.

### ***Data Analysis Technique***

The data analysis technique used in this study utilized the qualitative description method, which had three steps. The literature was initially identified and chosen based on its relevance to the research topic. The second is literature classified by key themes, including the value of AR in education, implementation challenges, and future expansion prospects. Thereafter, data analysis and interpretation were conducted to provide insights into strengths, weaknesses, and recommendations in formulating AR for lightwave education (Budiarti et al., 2020). From the title of this paper, there were 34 articles derived from the title, but there were only 19 articles that are within the category, which include augmented reality as learning media, augmented reality as a learning module, augmented reality as LKPD, and augmented reality in general

## RESULTS AND DISCUSSION

The research data included in this literature review are an analysis and summary of articles on the use of Augmented Reality as an interactive learning medium for light-wave materials.

Table 2. Mapping research results and critical analysis of studies on Augmented Reality (AR)-Based learning media

| No. | Researcher                    | Article name   | Research results  | Critical Analysis<br>(Comparison & Patterns)  | Research gap   |
|-----|-------------------------------|--|---|---|--|
| 1.  | (Socrates & Mufit, 2022)      | Effectiveness of Augmented Reality-Based Physics Learning Media Implementation: A Literature Study         | This research confirms that AR-based learning media are effective at creating an engaging and meaningful learning experience, especially for abstract physics concepts. | Supported also by Teichrew & Erb (2020) and Vidak et al. (2024), showing consistency of the positive effect of AR on abstract concepts. | Does not explain the cognitive mechanisms behind AR's effectiveness; it focuses only on learning outcomes. |
| 2.  | (Pauziah & Laksanawati, 2023) | Development of Physics Learning Media Based on Augmented Reality on Crystal Structure Material             | This research emphasizes the importance of innovation in education through the use of AR technology.  | Conceptual discussion only, without empirical validation.   | Needs experimental research to measure how much AR-based innovation improves learning.                     |
| 3.  | (Juwita et al., 2021)         | Augmented Reality (AR) Technology as a Science Learning Media Solution in the New Normal Adaptation Period | This research is needed to explore the effect of AR on student learning outcomes and to develop better AR applications in education.                                    | Emphasizes the need for technology but lacks outcome data.  | No quantitative measurement of learning or motivation effects.   |
| 4.  | (Ashari, 2023)                | Analysis of the Utilization of Augmented Reality (AR) Learning Media to Improve Critical Thinking Skills   | This article emphasizes the importance of integrating technology, particularly Augmented Reality, into physics education to meet modern learning demands.               | In line with Mashami et al. (2021) and Fajari & Meilisa (2022).   | Does not clearly specify the assessment instruments for critical thinking.                                 |
| 5.  | (Dewi & Anggaryani, 2020)     | Making Physics Learning Media with Android-Based Augmented Reality on                                      | This research shows that Augmented Reality (AR)-based learning media for optical devices is effective in  | Similar to Mulyati et al. (2019) and Amalia et al. (2020), which also focus on optics and light.  | Topic too narrow; needs application to other physics concepts.   |

|    |                          |   |   |  |   |
|----|--------------------------|---|---|--|---|
|    |                          | Optical Equipment Material  | improving students' understanding, despite some challenges related to object stability when the camera is moving.   |  |   |
| 6. | (Mashami et al., 2021)   | Development of Contextual Learning Module Integrated with Augmented Reality to Improve Students' Critical Thinking Skills                           | This research successfully developed a chemistry learning module integrated with AR technology, which proved effective in improving students' understanding of chemical bonding and their critical thinking skills. | Shows potential across different disciplines beyond physics.           | Lacks cross-disciplinary validation and transfer-of-learning tests.                       |
| 7. | (Fajari & Meilisa, 2022) | The Development of Augmented Reality to Improve Critical Thinking and Digital Literacy Skills of Elementary School Students                         | This study shows that AR learning media is effective in improving critical thinking skills and digital literacy of elementary school students.  | Confirms the general trend: AR enhances critical thinking.             | No comparative studies across education levels (elementary, high school, and university). |
| 8. | (Ariadi et al., 2023)    | Implementation of Excellent Learning Model and Augmented Reality Media to Improve Students' Critical Thinking Skills                                | This research shows that using an Excellent learning model with innovative approaches can effectively improve students' critical thinking skills and achievements. This is a classroom action study.                | One of the few studies integrating AR with a pedagogical model.        | Needs comparison among models (e.g., PBL, inquiry, and Excellent) using the same AR tool. |
| 9. | (Q. Amalia et al., 2025) | The Effect of Visual Thinking Strategy in Augmented Reality (ViTSAR) to Improve Students' Reflective Thinking Skills on the Material of Light Waves | This study demonstrates that using ViTSAR media has a remarkable effect on students' reflective thinking skills compared to traditional teaching methods.   | Innovative integration of the <i>visual thinking strategy</i> with AR. | It should be extended to critical thinking skills, not only reflective ones.              |

- |     |                        |   |  |   |   |
|-----|------------------------|---|--|---|---|
| 10. | (Wibowo, 2023)         | Effects Of Augmented Reality Integration (Ari) Based Model Physics Independent Learning (Mpil) For Facilitating 21st-Century Skills (21-Cs) | This research illustrates that ARI technology positively impacts learning motivation and 21st-century skills of marine physics students.   | Focuses more on soft skills than academic performance.                    | Needs integrative studies linking motivation, critical thinking, and achievement. |
| 11. | (Teichrew & Erb, 2020) | How augmented reality enhances typical classroom experiments: examples from mechanics, electricity, and optics                              | The results show that AR not only increases students' understanding but also encourages active engagement in the learning process, which can, in turn, lead to better learning outcomes. | Strong evidence supporting <i>active learning through AR</i> .            | No investigation of long-term retention or transfer effects.                      |
| 12. | (Al-Ansi et al., 2023) | Analyzing augmented reality (AR) and virtual reality (VR) recent development in education   | The argument points out that AR and VR have the potential to revolutionize the practice of teaching through interactive learning experiences.  | Provides a broad theoretical framework for AR/VR.                         | Lacks specific focus on physics and detailed pedagogical effects.                 |
| 13. | (Ding et al., 2023)    | Waveguide-based augmented reality displays: perspectives and challenges   | This research illustrates that, despite significant advancements, challenges in efficiency, image quality, and fabrication complexity remain.  | Offers valuable technical insights rarely discussed in education studies. | Requires studies that link technical performance to learning outcomes.            |
| 14. | (Mulyati et al., 2019) | The design of sound waves and optical markers for physics learning based on augmented reality technology                                    | The article emphasizes the potential of AR to augment physics learning by visualization and interactive learning processes.  | Demonstrates how 3D visualization supports mental model building.         | Does not explore students' cognitive load when using AR.                          |
| 15. | (Vidak et al., 2024)   | Augmented reality technology in teaching about physics: a systematic  | The discussion shows that although AR has vast potential to augment physics learning, it must be   | Aligns with <i>Cognitive Load Theory</i> .                                | Needs empirical testing of cognitive load in AR-based learning.                   |

|    |                       |   |  |  |   |
|----|-----------------------|---|--|--|---|
|    |                       | review of opportunities and challenges  | implemented cautiously to avoid cognitive problems.  |  |   |
| 16 | Amalia et al., 2020)  | Development of Interactive Learning Media on Light Waves Material Based on Android Using Articulate Storyline 3 | The thesis in this study emphasizes the importance of incorporating technology into education to improve students' learning processes and outcomes.  | Not AR-based but useful for comparison.                                | Can serve as a control group media (2D) for AR comparison studies.                      |
| 17 | (Minaee et al., 2022) | Modern Augmented Reality: Applications, Trends, and Future Directions   | The paper focuses on significant developments in AR and deep learning technologies and their applications in real-world settings across industries.  | Highlights the future potential of AR in multiple industries.          | Requires implementation research on AI-AR in physics education.                         |
| 18 | (Garzón, 2021)        | An Overview of Twenty-Five Years of Augmented Reality in Education  | Studies reveal that, despite significant advancements in AR technology, there remains a need to address accessibility, usability, and pedagogical applicability concerns to maximize its use in learning spaces. | Reinforces global concern about access and sustainability of AR tools. | Major gap: limited inclusivity and accessibility across different educational settings. |

Based on the above research results, there are several augmented-reality categories in Physics learning. The use of augmented reality (AR) as an interactive learning medium will be the mainstay for concept understanding and students' success in learning, especially in the light waves subject. Table content will be explained if necessary because the research purpose is explained in the Introduction section. Augmented Reality technology enables students to interact with virtual objects in space, making intangible content, such as waves of light, more concrete and interactive. This allows students to have a more concrete conceptual framework and to eliminate leading misconceptions during the learning process of physics.

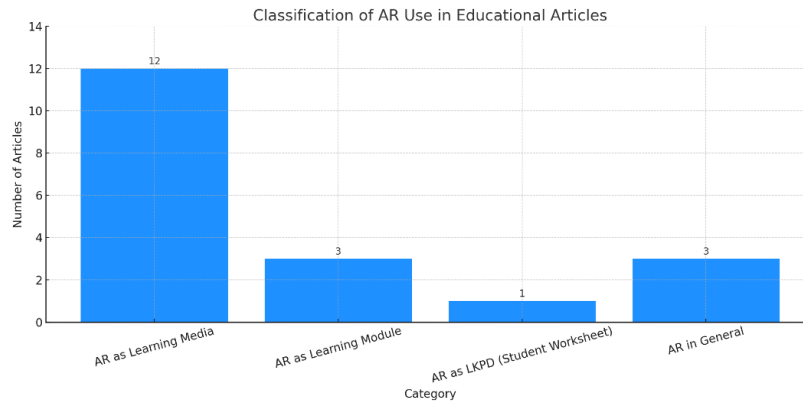


Figure 2. Classification of AR use in educational articles

Various AR-based learning packages have been designed to enable enhanced and more interactive learning (Al-Ansi et al., 2023). With interactive animation and three-dimensional visualization, the student can view phenomena such as refraction, reflection, diffraction, and interference of light in a simulated, real-life setting (Juwita et al., 2021). The interactivity of these technologies allows students to conduct virtual experiments, substitute variables, and see firsthand the impact of these variables on light-wave phenomena, which was challenging to do using traditional methods alone (Ding et al., 2023).

In line with Cognitive Load Theory and Constructivist Learning Theory, AR facilitates learners' mental model construction by reducing cognitive barriers and engaging them in active exploration (Vidak et al., 2024; Teichrew & Erb, 2020). The 3D visualization and interactivity of AR directly support meaningful learning, where students construct knowledge through experience rather than passive observation (Hidayat et al., 2024). This theoretical alignment explains why AR consistently improves understanding of abstract concepts such as light refraction and diffraction.

In addition to improving concept understanding, learning through augmented reality also fosters the development of 21st-century skills, especially 4C skills: creativity, critical thinking, collaboration, and communication. Through discovery and collaborative exercises with AR media, students are invited to think critically about phenomena, be creative in solving problems, and communicate and work together in learning groups (Ardiyanti & Nuroso, 2021). Thus, the integration of AR in learning not only improves students' cognitive abilities but also skills and attitudes relevant to today's educational needs.

### **The Use of Augmented Reality in Light Wave Learning**

Augmented reality (AR) technology is increasingly used in education, including in physics learning, especially for light-wave materials (Socrates & Mufit, 2022). AR enables students to visualize abstract physical phenomena more concretely, helping them understand complex concepts more easily. AR-based physics learning media are effective in improving understanding of abstract concepts because they can present the phenomenon of light waves visually and interactively (Ashari, 2023). Augmented reality in physics learning opens up great opportunities to enrich learning experiences, especially in teaching optics and wave concepts (Vidak et al., 2024). They emphasized that the advantage of AR lies in its ability to provide real, simulation-based learning experiences without conducting expensive or risky physical experiments. The integration of AR into traditional physics lab experiments, for example, in optics, can improve students' engagement and understanding (Teichrew & Erb, 2020).

The consistency of these findings across multiple studies (e.g., Teichrew & Erb, 2020; Guntara et al., 2023; Wibowo, 2023) demonstrates a robust trend that AR promotes active learning and cognitive engagement, aligning with experiential learning theory (Bramastia & Rahayu, 2023). This theoretical grounding strengthens the conclusion that AR effectively bridges the gap between abstract scientific representations and students' perceptual understanding.

The use of 3D AR learning media can increase students' motivation to learn (Carolina, 2023). By fostering a more interactive learning atmosphere, students are more passionate about learning about light wave phenomena, including refraction, interference, and diffraction. Visual Thinking Strategy in AR (ViTSAR) in light-wave material has been shown to improve students' reflective thinking abilities

(Guntara et al., 2023). AR for learning sound and light waves, and found that the use of these markers can clarify simple wave ideas better through efficient but basic visual communication (Mulyati et al., 2019). Technologically, it discusses the development of waveguide-based display devices for AR that enable a more realistic, high-quality visual display of AR content, a major contributor to light-wave learning that requires precision in visual observation (Ding et al., 2023).

This is also supported by Wibowo's (2023) research, which states that the use of AR-based learning models can improve students' 21st-century skills, including critical thinking, problem-solving, and teamwork, skills that are also needed to understand and apply the concept of light waves in real-world situations. The application of ViTSAR significantly improves students' reflective thinking skills related to light wave content. Based on this statement, Facione (2011) identified six main components of critical thinking, namely interpretation, analysis, evaluation, inference, explanation, and self-regulation. Students not only understand concepts but also learn to analyze, evaluate, and reflect on their learning experiences in greater depth (Amalia et al., 2025).

### **Advantages and Benefits of Augmented Reality**

Augmented reality (AR) technology offers several benefits that make it a valuable tool in education today. Perhaps the most important benefit of AR is its ability to present interactive three-dimensional visualizations, which can help students understand abstract concepts such as crystal structures and optical equipment in physics education (Pauziah & Laksanawati, 2023). With this technology, not only are the students visually engaged, but they are also mentally engaged, as learning object interaction directly provokes active engagement. From a theoretical standpoint, AR enhances dual-channel learning by combining visual and auditory stimuli. Empirical findings (Mashami et al., 2021; Fajari & Meilisa, 2022) reinforce that AR contributes to deeper understanding, longer retention, and improved critical thinking performance.

In addition, AR has been shown to improve students' critical thinking and digital literacy, which are essential skills in the 21st century (Ashari, 2023; Fajari & Meilisa, 2022; Mashami et al., 2021). AR can also improve a more engaging and enjoyable learning experience, so students will learn more actively and engage with the learning process (Juwita et al., 2021). Another study finds that the use of AR leads to improved learning performance and knowledge retention because knowledge conveyed in a multimodal format is more understandable and memorizable (Socrates & Mufit, 2022). In Fisher (2011), Robert Ennis explains that critical thinking is about making a decision. Ennis asserts that critical thinking relates to a person's ability to give honest advice when they need to formulate a position. Ennis defines critical thinking as a reflective, focused approach to determining appropriate beliefs and actions. In this context, critical thinking supports a structured, logical process for reaching sound conclusions.

The second benefit is the easy integration of AR with various learning models, such as contextual learning and inquiry, thereby consolidating AR as adaptive learning media that accommodates various pedagogies (Mashami et al., 2021). Being full of autonomous and collaborative learning characteristics, AR not only enhances the quality of learning but also adds convenience and accessibility in gaining information. Practically, AR has been shown to improve classroom motivation and student autonomy, providing teachers with new tools for differentiated instruction. It also integrates easily with inquiry, contextual, and problem-based learning models (Mashami et al., 2021), making it a flexible tool adaptable to diverse pedagogies.

### **Challenges of Augmented Reality Implementation**

Augmented reality (AR) technology has numerous advantages for educational applications, but it also faces significant challenges. One of the major problems is the limited availability of hardware and technological infrastructure, especially in schools with inadequate technological facilities (Juwita et al., 2021). Additionally, readiness in human resources, specifically teachers and educators, remains a principal impediment. The majority of these instructors have never received training on the use or development of AR-based learning materials, hence the necessity for intense training and technical support (Kalsum et al., 2023; Socrates & Mufit, 2022).

The other problem is that augmented reality content is still not fully standardized and only accessible for certain topics, such as in the study of crystal structure learning media production (Pauziah & Laksanawati, 2023). Technical restrictions, such as the requirement for a stable internet connection

and the potential for errors in Augmented Reality applications, also often hinder the seamless learning process (Teichrew & Erb, 2020). Furthermore, students' tendency to be distracted by AR's visual content diminishes focus on the core material, contrary to pedagogical aims.

Globally, international studies identify the need to improve digital literacy and problem-solving among educators to effectively integrate new technology (Cai & Gut, 2020). Other technical challenges arise in the design of waveguide-based AR devices, which offer a better user experience but are comparatively expensive and complex to implement widely (Ding et al., 2023). Apart from this, there are some novel approaches, such as the Visual Thinking Strategy in AR (ViTSAR), which prioritizes designing learning experiences that are not only visually pleasing but also elicit reflection and critical thinking (Guntara et al., 2023).

Previous research suggests that the use of Augmented Reality (AR) as an interactive learning tool is effective in helping students understand abstract light-wave phenomena such as reflection, refraction, and interference (Guntara et al., 2023). AR allows visualization of ideas in three dimensions, thereby increasing student motivation, engagement, and understanding compared to traditional methods (Kalsum et al., 2023). Although barriers such as special equipment and teacher training needs remain, in general, the literature supports AR as a revolutionary remedy for learning physics, especially for content on light waves (Ardiyanti & Nuroso, 2021).

### **Analysis of the Advantages of AR in Light Wave Learning**

The use of augmented reality (AR) in the study of light waves offers significant advantages. Its ability to visualize abstract phenomena such as reflection, refraction, diffraction, and interference, which are difficult to depict with text or two-dimensional pictures alone, is one of its main benefits. AR offers three-dimensional interactive simulations that allow students to explore light phenomena in real, interactive terms (Ariadi et al., 2023).

Furthermore, AR has been found to improve students' participation and engagement in the learning process. This media facilitates active and discovery-based approaches to learning, enabling students to watch, predict, and draw conclusions from the results of their inquiry (Utami et al., 2024). In science learning, this resonates with the development of critical thinking and problem-solving capabilities. Moreover, AR facilitates independent learning by allowing learners to learn at their own pace and in their own style. The application of this technology not only improves comprehension of concepts but also develops curiosity and motivation for learning (Putri et al., 2024). Other research shows that integrating AR with learning approaches such as PjBL (Project-Based Learning) and Problem-Based Learning can benefit students' learning outcomes and science attitudes (Wahyuni, 2020).

Augmented Reality also has potential for virtual practicum, especially useful when laboratory facilities are limited. For example, the use of AR to visualize light interference can replace expensive and complex optical equipment while preventing experimental mistakes (Q. Amalia et al., 2025). While learning geometric optics, AR allows learners to view the directions of incident and refracted rays from various angles (Utami et al., 2024). In addition to in-class learning, AR is successfully applied in an experimental physics practicum.

### **Augmented Reality Limitations Analysis**

The application of augmented reality (AR) in education has significantly enhanced learning processes and results. Another significant advantage of AR is that it is able to represent abstract information visually and interactively in a way that it can be easily understood by students, such as crystal structure or molecular geometry (Pauziah & Laksanawati, 2023). AR also has the potential to boost students' motivation to learn and engagement because it is fun and intellectually stimulating (Guntara et al., 2023; Juwita et al., 2021).

Augmented reality (AR) is an important educational innovation, mainly due to the fact that it allows for the visualization of abstract concepts. Its use is not without limitations that need to be considered. Inadequate infrastructure, for example, the unavailability of sufficient hardware in the majority of schools, especially in low-resource contexts (Juwita et al., 2021), is a significant challenge. Also, the lack of technological skills among teachers hinders the effective use of AR (Kalsum et al., 2023), a finding corroborated by the results of a literature review conducted by Socrates & Mufit (2022), which states that teacher training remains minimal. In terms of content, AR is not always fully aligned

with the national curriculum or focuses only on particular subjects, such as crystal (Pauziah & Laksanawati, 2023), and therefore, its scope remains narrow.

From a pedagogical point of view, AR can be distracting because of its largely visual orientation, which can cause students to lose sight of the core learning objectives. Technical issues are also a significant hindrance; AR applications require a constant internet connection and powerful software, which cannot be guaranteed at all times (Gustini & Wulandari, 2020). Apart from that, creating AR applications is costly during content creation, coding, and testing (Socrates & Mufit, 2022). However, several studies concur on the effectiveness of AR when used appropriately and harmoniously integrated with effective pedagogies (Juwita et al., 2021; Pauziah & Laksanawati, 2023).

### **Study Limitations**

This study is limited by the scope of the selected literature (2019–2025), the predominance of descriptive studies over experimental ones, and the limited focus on light-wave materials compared to broader physics topics. Additionally, publication bias may exist, as studies reporting positive outcomes of AR are more likely to be published. Future research should employ longitudinal and mixed-method designs to assess AR's long-term effects, integrate cross-disciplinary validation, and explore the role of AI–AR combinations in personalized physics learning

### **CONCLUSION**

The use of augmented reality (AR) technology in education, especially in physics, is an innovative solution to bridge the gap in students' understanding of abstract concepts such as light waves. AR provides an immersive, interactive, and three-dimensional visual-based learning experience, thereby improving conceptual understanding, critical thinking skills, and student learning motivation. Based on literature reviews from various national and international sources, it is evident that the use of AR in learning can encourage active student involvement and mastery of 21st-century competencies, such as collaboration and problem-solving. However, the application of this technology still faces several obstacles, including limited facilities, insufficient teacher training, and the need for content development aligned with the curriculum. Therefore, AR has great potential to be integrated as an innovative learning medium that is relevant in the digital era, provided that it is supported by resource development, continuous educator training, and synergy between technology developers and education policymakers. Future research is recommended to explore the long-term impact of AR on students' cognitive and affective outcomes, to develop adaptive AR platforms personalized to different learning levels, and to examine the integration of AR with emerging technologies such as artificial intelligence (AI) or virtual laboratories.

For practical implementation, teachers are encouraged to start with topic-specific AR modules that visualize light-wave phenomena, such as reflection, refraction, and interference, to promote deeper understanding. Educational technology developers should collaborate with educators to design curriculum-aligned, user-friendly AR content that supports inquiry-based and problem-solving learning models. By addressing these aspects, the integration of AR into physics learning can become more sustainable, pedagogically meaningful, and more effective at nurturing students' critical and creative thinking skills.

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