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THE 21ST CENTURY EDUCATION: A SYSTEMATIC LITERATURE REVIEW OF TRANSFORMING LEARNING METHODS TO FOSTER CRITICAL THINKING SKILLS THROUGH AUGMENTED REALITY IN SCIENCE LEARNING

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Abstract
This study aims to examine the potential of augmented reality in enhancing science learning, with a particular focus on physics learning. It involves a qualitative synthesis of previous research, incorporating both quantitative and qualitative studies, that explores instructional designs using augmented reality in science learning and its effects on students' critical thinking skills. The study analyzes articles published between 2014 and 2023 in the Scopus database, with 46 articles selected for in-depth analysis and synthesis. The findings indicate that integrating augmented reality in science learning can enhance students' thinking skills, particularly critical thinking skills. The use of learning models such as discovery learning, problem-based learning, and inquiry-based learning can make learning more meaningful and increase student engagement in the learning process. No studies have been identified that assess multi-representation skills in science learning through augmented reality. Further research is essential to investigate the specific effects of augmented reality media on students' multi-representation skills.
Keywords: augmented reality, critical thinking skills, physics learning

Abstrak
Penelitian ini bertujuan untuk mengkaji potensi augmented reality dalam meningkatkan pembelajaran sains, dengan fokus khusus pada pembelajaran fisika. Studi ini melibatkan sintesis kualitatif dari penelitian sebelumnya, mencakup studi kuantitatif dan kualitatif yang mengeksplorasi desain pembelajaran menggunakan augmented reality dalam pembelajaran sains serta pengaruhnya terhadap keterampilan berpikir kritis siswa. Penelitian ini menganalisis artikel yang diterbitkan antara tahun 2014 hingga 2023 dalam basis data Scopus, dengan 46 artikel yang dipilih untuk analisis mendalam dan sintesis. Temuan menunjukkan bahwa integrasi augmented reality dalam pembelajaran sains dapat meningkatkan keterampilan berpikir siswa, terutama keterampilan berpikir kritis. Penggunaan model pembelajaran seperti discovery learning, problem-based learning, dan inquiry-based learning dapat membuat pembelajaran lebih bermakna dan meningkatkan keterlibatan siswa dalam proses pembelajaran. Tidak ada penelitian yang teridentifikasi yang menilai keterampilan multi-representasi dalam pembelajaran sains melalui augmented reality. Penelitian lebih lanjut sangat diperlukan untuk menyelidiki efek spesifik media augmented reality

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INTRODUCTION

21st-century education demands a transformation in learning methods to align with technological advancements and the competency needs of students. One crucial competency that must be developed in this modern era is critical thinking skills. Critical thinking skills are one of the four key competencies required in the 21st century, alongside communication, collaboration, and creativity (Achmad & Utami, 2023; Marisda et al., 2024). Willingham (2007: 11) explains that critical thinking involves "critical reasoning, decision-making, and problem-solving." Meanwhile, Ennis (1989: 4) defines critical thinking as "rational reflective thinking focused on decisions about what should be believed or done." Students need to develop critical thinking skills during the learning process (Ariani, 2020; Maison et al., 2022). This skill helps students understand, analyze, and evaluate information (Maknun, 2020; Spector & Ma, 2019) to achieve the desired learning outcomes (Darmaji et al., 2020). Therefore, critical thinking can be considered one of the essential competencies that students must master in the 21st century.

Critical thinking skills are considered essential for addressing workplace challenges, solving complex problems, and making informed decisions based on relevant information (Ku, 2009; Halpern, 2013; Facione, 2015). Unfortunately, research indicates that the development of critical thinking skills in schools remains suboptimal, particularly in the fields of science and physics (Henderson et al., 2015; Sundari & Sarkity, 2021; Asniar et al., 2022). One potential solution that has emerged is the utilization of Augmented Reality (AR) technology in learning. Augmented reality (AR) is a form of media that helps establish a digital learning environment (Sousa & Rocha, 2019; Wulandari et al., 2021). It is a digital technology that generates virtual content, such as images, through a computer or mobile device, which is then overlaid onto the real world in real-time. This content can include three-dimensional (3D) models, images, videos, sound, and text (Lee, 2012). Today, AR is widely used in educational settings.

Ideally, physics and science learning should facilitate students' understanding of abstract concepts, for instance, through experimental activities (Directorate-General for Research and Innovation, 2007; Zacharias & Constantinos, 2008; Bigozzi et al., 2018; Eva & Josef, 2021; Toli & Kallery, 2021). However, in practice, many students struggle to grasp these concepts due to limitations in equipment, environment, and conventional teaching methods (Bower et al., 2014; Sadler & Sonnert, 2016; Bigozzi et al., 2018). For example, physics experiments in traditional classrooms are often constrained by the availability of laboratory equipment, time, and safety risks. Yet, student engagement in experimental activities is believed to enhance concept comprehension (Bigozzi et al., 2018; Banda & Nzabahimana, 2021), academic performance (Chiang et al., 2014; Sshana & Abulibdeh, 2020), motivation (Chiang et al., 2014), higher-order thinking skills (Antonio & Prudente, 2024), critical thinking skills (Komariyah & Karimah, 2019; Kotsis, 2024), and problem-solving abilities (Kotsis, 2024). This is where AR technology can play a vital role by offering interactive simulations that allow students to learn through direct experience without physical limitations.

Previous study has extensively investigated the application of AR in education, with several studies indicating that AR can boost student motivation, aid in understanding abstract concepts, and heighten student engagement in the learning process (Cheng & Tsai, 2013; Chiang et al., 2014; Ibáñez & Delgado-Kloos, 2018). However, studies specifically examining the effects of AR on improving critical thinking skills within science learning, particularly in physics, are still limited (Wibowo, 2023). This gap highlights

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the need for further exploration into the relationship between AR and the development of students' critical thinking skills within science and physics learning.

This study proposes a systematic review of the existing literature in the Scopus database to identify the extent to which AR has been utilized in physics and science learning, as well as its impact on students' critical thinking skills. Data were collected and reduced using the PRISMA method, then synthesized in depth and presented in the form of tables, diagrams, and visualized through network visualization using VOSviewer. The implications of this study are vast in the field of education, particularly at the educational level that studies science subjects, such as physics. The use of AR can not only enhance students' understanding of challenging physics concepts but also has the potential to equip them with improved critical thinking skills, which are essential in today's global era (Komariyah & Karimah, 2019; Kotsis, 2024). In the context of physics learning, AR can assist students in visualizing abstract phenomena such as magnetic fields or particle motion, enabling them to analyze these concepts more critically (Wibowo, 2023). Additionally, AR can create a more contextual learning environment, helping students connect lessons to real-life situations relevant to their daily experiences (Chen et al., 2021; Salira et al., 2024).

Thus, through this research, it is hoped that a more comprehensive guide will be produced on how AR technology can be integrated into the physics and science curriculum to not only enhance students' understanding of the material but also significantly develop their critical thinking skills. The following research questions will be addressed in this study:

1) In the process of science and physics learning, what aspects can AR be used to enhance?
2) Does the use of AR improve critical thinking skills?
3) What types of AR are commonly used in science and physics learning?
4) How is the relationship between AR and critical thinking skills analyzed using VOSviewer?

METHOD

This study uses a literature review approach to collect information from numerous prior studies related to the application of AR technology in science learning. The data comprises secondary sources, including research findings published in international journals available in the Scopus database. A qualitative analysis is applied to the data, focusing on words and descriptions rather than numerical data. The data analysis process follows the steps outlined by Miles and Huberman (Fraenkel et al., 2018), as presented in Figure 1 below:

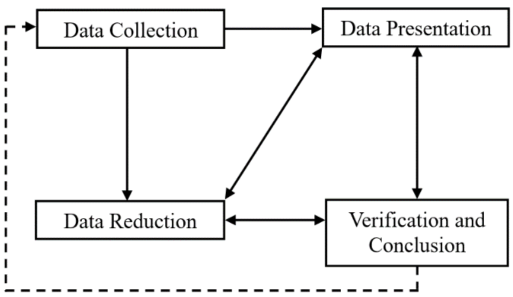

Figure 1. Process of Data Analysis According to Miles and Huberman

The first step in the qualitative data analysis is to gather articles from the Scopus database to obtain relevant data and information for the research. Next, the data reduction phase is carried out by summarizing, selecting key points, and focusing the discussion to make the obtained data clearer and facilitate the researcher's understanding. Afterward, the data presentation is done by organizing a narrative text in the form of a brief description that illustrates the relationship between the subjects and related elements. The final step in qualitative data analysis is drawing conclusions and verification.

In the data collection and data reduction phases, the researcher uses the PRISMA method, which consists of four stages: identification, screening, eligibility, and inclusion. The article search process begins by using keywords such as "Augmented Reality" AND "Science Education," filtering relevant articles, and selecting those that meet the research criteria. In this study, the articles were synthesized based on the following criteria: (1) published in Scopus-indexed journals, (2) discussing the use of AR in science education, (3) published between 2014 and 2023, (4) written in English, (5) not conference proceedings, (6) not literature reviews, and (7) open access. The detailed article selection criteria are presented in Table 1.

Table 1. Criteria for Article Selection

Criteria	Inclusion	Exclusion
Journal Source	Published in Scopus-indexed journals	Not published in Scopus-indexed journals
Study	The study discusses the use of Augmented Reality in science learning.	The study does not discuss the use of Augmented Reality in science learning.
Period	Published between 2014 and 2023	Not published between 2014 and 2023
Document Type	Article	• Literature review • Conference paper/proceedings • Book • Book Chapter
Languange	English	Not using English
Open Access	All Open Access	Not Open Access
Publication Stage	Final	In Press

The initial search in the Scopus database identified 297 documents related to Augmented Reality in science education (keywords used: "Augmented Reality" AND "Science Education"). To narrow the scope, the search was limited to publications from 2014 to 2023, resulting in 229 documents. Further screening was conducted based on the following criteria: 1) open access and English language (74 documents), 2) exclusion of conference proceedings, review articles, and literature studies (54 documents), and 3) inclusion of articles discussing Augmented Reality in science and physics learning. After applying these eligibility steps, the final systematic review included 46 articles in the data extraction phase, which are explicitly related to Augmented Reality in science learning. This process is summarized using the PRISMA framework in Figure 2.

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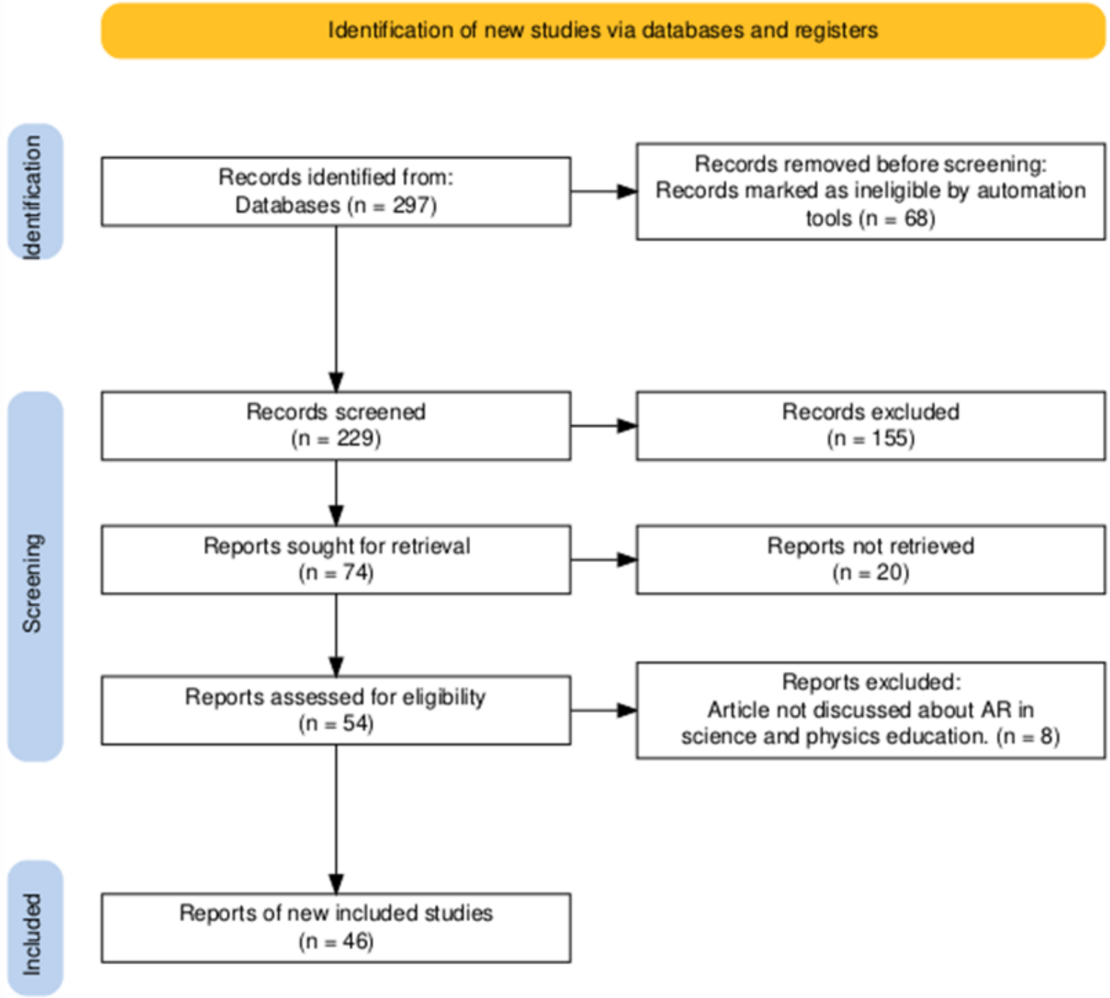

Figure 2. PRISMA Model for Reduction Articles

The data from each reviewed article is analyzed based on specific aspects that align with the indicators set by the reviewers, including the research subject area, research type, learning activities, variables studied, findings, topics explored, and types of augmented reality used in studies related to science and physics learning. The collected data is presented in tables and bar charts. Additionally, data from Scopus is stored in RIS format and then visualized using VOSviewer to analyze the relationships between titles and abstracts, followed by interpretation.

RESULT AND DISCUSSION

Result

In this review, the selected studies are analyzed to answer the research questions related to the use of Augmented Reality in science education. Each piece of data is thoroughly examined to extract detailed information from the systematically chosen articles. The collected data is then analyzed and presented in tables. The data extraction results include the authors' names, research areas, research methods used, learning activities applied in Science education, research variables measured, and the key findings of the studies. A detailed analysis is also conducted to identify the types of Augmented Reality used, as well as the learning topics most commonly utilizing AR, particularly in physics education. A comprehensive explanation of the emerging trends from the reviewed studies is provided to address the four main research questions. A total of 46 articles were selected based on the criteria set by the authors, which were then synthesized in detail, with the synthesis results presented in Table 2.

Table 2. Summary of 46 Synthesized Articles

No.	Author	Subject Area	Research Type
1.	Abdullah et al., 2022	Science Education	Quasi-experimental research
2.	Abriata, 2022	Chemistry and Biology Education	Descriptive-qualitative research
3.	Alkhabra et al., 2023	STEAM Program	Experimental research
4.	Bakri et al., 2020	Physics Learning	R&D
5.	Bidarra & Rusman, 2017	Science Education	Descriptive-qualitative research
6.	Cai et al., 2021	Physics Learning	Quasi-experimental research
7.	Cai et al., 2022	Science Learning	Qualitative case study
8.	Chen, 2022	Science Learning	Quantitative research
9.	Cheng, 2018	Science Learning	Qualitative survey research
10.	Chiu et al., 2019	Chemistry Education	Qualitative research
11.	Czok et al., 2023a	Science and Engineering Teaching	Quasi-experimental research
12.	Czok et al., 2023b	Science and Engineering	R&D
13.	Daineko et al., 2022	Physics Learning	R&D
14.	Damopolii et al., 2022	Science Learning	R&D
15.	Demircioglu et al., 2023	Science Classes (Astronomy)	Qualitative case study
16.	Fearn & Hook, 2023	Science Education	Design-based research
17.	Fleck & Hachet, 2016	Astronomy	Experimental research
18.	Fleischer et al., 2023	Science Classrooms (Chemistry)	Exploratory qualitative study
19.	Gopalan et al., 2015	Science Learning	Quantitative evaluation
20.	Gopalan et al., 2020	Science Experiment	R&D
21.	Hsu et al., 2023	Biology	Qualitative case study
22.	Kapp et al., 2022	STEM Education (Electrical Experiment)	Quasi-experimental research
23.	Karagozlu & Ozdamli, 2017	Science Learning	Design-based research
24.	Karagozlu et al., 2019	Science Classes	Qualitative study
25.	Karagozlu, 2021	Science Education	Quantitative research
26.	Kececi et al., 2021	Science Teaching	Mixed-methods
27.	Kirikkaya & Başgül, 2019	Science Learning	Quasi-experimental research
28.	Krug et al., 2023	Science Education	Quasi-experimental research
29.	Lai et al., 2019	Science Learning	Experimental research
30.	Nasir & Fakhruddin, 2023	Physics Learning	R&D
31.	Özerbaş, 2019	Science Education	Quasi-experimental research
32.	Rahmat et al., 2023	Physics Learning	Mixed methods
33.	Rejekiningsih et al., 2023	Science Learning	Descriptive-qualitative research
34.	Rizki et al., 2023	Physics Learning	R&D
35.	Ropawandi et al., 2022	Physics Learning	Quasi-experimental research

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36.	Sulisworo et al., 2021	Science Learning	Action research
37.	Suprapto et al., 2020	Physics Learning	R&D
38.	Suprapto et al., 2021	Physics Learning	R&D
39.	Syawaludin & Rintayati, 2019a	Science Learning	R&D
40.	Syawaludin & Rintayati, 2019b	Science Learning	Classroom action research
41.	Techakosit & Nilsook, 2016	STEM Education	R&D
42.	Thees et al., 2022	Physics Laboratory	Comparative study
43.	Tu et al., 2023	Science Learning	Exploratory qualitative study
44.	Vega Garzón et al., 2017	Biochemistry	R&D
45.	Wen et al., 2023	Science Learning	Quasi-experimental research
46.	Wibowo et al., 2023	Physics Learning	Quasi-experimental research

Augmented Reality is a rapidly evolving technology applied in various educational fields, including mathematics and science, recognized for its effectiveness in enhancing teaching strategies (Martin-Gonzalez et al., 2015) and enhancing student engagement through immersive learning experiences (Arici et al., 2019). As shown in Table 2, AR has been extensively incorporated into educational settings, particularly within science disciplines such as physics, chemistry, biology, and engineering. This technology enhances "reality" by overlaying digital elements—such as 2D or 3D models, animations, or simulations, often with sound—onto the physical world (Saltan & Arslan, 2017). Table 2 further indicates that the most common research methodology in AR studies is R&D, frequently utilizing an experimental-quasi design. This study review aims to examine the connection between AR-based activities in science or physics learning, the variables assessed, and their impact on learning outcomes. A synthesis of 25 selected articles is provided in Table 3.

Table 3. Summary of 25 Synthesized Articles

No.	Author	Leaning Activity	Research Variable	Findings
1.	Alkhabra et al., 2023	AR-based active learning	Learning retention and critical thinking skills	AR positively impacts learning retention and critical thinking skills.
2.	Bakri et al., 2020	Discovery learning	Conceptual understanding	Moderate improvement in student knowledge with an n-gain score of 0.46.
3.	Cai et al., 2022	Inquiry-based learning with framework QIMS	Students' concepts of learning science and scientific epistemic beliefs	Students generally have positive conceptions of learning science and high scientific epistemic beliefs.
4.	Chen, 2022	AR-based active learning	Self-efficacy, attitudes toward the environment, and environmental behavior	Students' science self-efficacy in learning can influence the sustainability of their environmental behaviors, but only through the mediating role of environmental attitudes.
5.	Chiu et al., 2019	Model-based learning approach	Students' understanding of chemical structures	These cards help students foster a stronger interest in learning and enhance their understanding of

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				symbols, chemical equations, properties, structures, and the transition between 2D and 3D representations.
6.	Czok et al., 2023a	Game-based learning	Motivation, engagement, and cognitive load	Although augmented reality (AR) imposes a relatively high cognitive load, it does not negatively impact learning outcomes. AR holds potential for enhancing student motivation and engagement.
7.	Damopolii et al., 2022	Online learning	Critical thinking skills	There was a notable enhancement in students' critical thinking skills, with 75% of students demonstrating considerable progress in critical thinking by the end of the learning session using comics as AR markers.
8.	Demircioglu et al., 2023	AR-based argumentation activities	Students' critical thinking skills and argumentation abilities	All groups participated in argumentation and generated strong arguments. Students' critical thinking skills improved up to the midpoint of the intervention, with variations in the frequency of critical thinking skills usage observed after this point.
9.	Fleck & Hachet, 2016	Inquiry-based learning with a hybrid approach	Students' perceptions of abstract concepts, participation in learning activities, and conceptual understanding	AR integration enhances students' understanding of abstract concepts by making difficult-to-see phenomena more tangible. For example, the Helios AR application improves students' understanding of celestial motion twice as effectively compared to conventional approaches.
10.	Fleischer et al., 2023	Inquiry-based learning with digital scaffolding	Students' changing perspectives between AR instructions and physical experiments	AR facilitates independent experiments with efficient viewpoint shifts, although teacher involvement remains necessary.
11.	Hsu et al., 2023	Inquiry-based learning	Teachers' understanding in integrating AR	AR enhances student engagement in biology but requires teachers to adapt inquiry-based teaching approaches.
12.	Kapp et al., 2022	Inquiry-based learning in STEM laboratory	The accuracy and ease of use of smart sensors in electrical experiments.	AR is effective in simplifying the visualization of complex concepts in electrical experiments; however, sensor integration requires high accuracy.
13.	Karagozlu & Ozdamli, 2017	Problem-based learning	Students' opinions on AR applications	AR content for science is rated effective by teachers and students.

14.	Karagozlu, 2021	Problem-based learning	Students' and teachers' perspectives on AR content	AR has been found to help students better understand science topics by providing more engaging visualizations and enhancing interaction during lessons.
15.	Nasir & Fakhruddin, 2023	Mobile learning based on AR	Student achievement in learning physics	Mobile multimedia learning based on AR can positively impact student achievement in physics learning.
16.	Rahmat et al., 2023	Mobile learning based on AR	Physics learning achievement and students' opinions on the use of AR technology	Penggunaan augmented reality pada pembelajaran fisika berpengaruh positif terhadap prestasi belajar fisika siswa.
17.	Rizki et al., 2023	Game-based learning	Validity and practicality of the "Adventuring Physics" game application	The developed "Adventuring Physics" application is rated as valid, practical, feasible, and reliable. The AR features in the game application aid students in visualizing abstract physics concepts, particularly magnetic fields.
18.	Ropawandi et al., 2022	Online learning	Conceptual understanding	AR can enhance students' understanding of electrical concepts, especially in online learning during the pandemic.
19.	Suprapto et al., 2021	Pocketbook-assisted learning	Student achievement	Student achievement improved after using an AR-based physics pocketbook, with an average gain score of 0.63, categorized as moderate. Male students outperformed female students following the use of AR.
20.	Syawaludin & Rintayati, 2019a	Learning with AR-based interactive multimedia	Critical thinking skills	Improvement in students' critical thinking skills after using ar-based interactive multimedia, indicated by a p-value of 0.002 (<0.05) in the paired sample t-test.
21.	Techakosit & Nilsook, 2016	Scientific Imagineering through AR	STEM literacy	Studies show a significant improvement in students' STEM literacy skills, particularly in critical thinking, problem-solving, and creativity.
22.	Thees et al., 2022	Laboratory activities	Extraneous cognitive load and students' conceptual understanding	AR helps reduce the split-attention effect by enhancing spatial coherence between virtual data and real components; however, it does not significantly improve learning outcomes compared to separate displays.

23.	Tu et al., 2023	Learning with STEP environment	Conceptual understanding	Students demonstrated a better understanding of the concept of matter and its transformations after participating in learning activities within the STEP environment.
24.	Wen et al., 2023	Inquiry-based learning *dengan* framework QIMS	Learning achievement, self-directed learning, creative thinking, critical thinking, and knowledge creation efficacy	While there was no substantial difference in academic achievement with AR usage, students' self-directed learning and creative thinking skills improved significantly after participating in inquiry-based QIMS lessons. The combination of AR and QIMS notably boosts students' critical thinking and knowledge creation efficacy. Additionally, in terms of academic outcomes, integrating QIMS and AR appears particularly advantageous for students with lower progress levels.
25.	Wibowo, 2023	Model Physics Independent Learning (MPIL)	Critical Thinking, Collaboration, Communication, dan Creativity	Incorporating ARI technology into physics learning greatly improves students' creative and critical thinking skills, particularly in ocean physics concepts. It also supports students in further developing communication and collaboration skills for problem-solving within the ARI application. Additionally, it boosts learning motivation, fostering enthusiasm for exploring physics concepts.

The type of AR created will inevitably affect the research variables measured. A deeper synthesis was conducted to identify the most commonly used types of AR in science learning, particularly in the context of physics learning. Table 4 outlines the physics content and types of AR developed in educational research over the past nine years, focusing on studies published internationally.

Table 4. Topics, Types of AR, and AR-Based Developments in Physics

No.	Author	Topic	Type of AR	Application
1.	Bakri et al., 2020	Quantities and Units, Concept of Measurement	AR Video and Simulation	SmART (Science Experiments with AR Technology)
2.	Cai et al., 2021	Wave-Particle Duality (Photoelectric Effect Simulation)	3D Simulation	AROSE (Augment Reality Optical Simulation Experiments)

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3.	Daineko et al., 2022	Measurement	3D Object and Simulation	EasyAR
4.	Kapp et al., 2022	Concept of Electricity in STEM Education (Electric Circuits)	2D object	Microsoft HoloLens 2
5.	Nasir & Fakhruddin, 2023	Mechanical Waves	3D Object	Mobile Augmented Reality (MAR)
6.	Özerbaş, 2019	Interaction of Light with Matter (Absorption and Refraction of Light)	3D Simulation	MBAR (Marker-Based Augmented Reality)
7.	Rahmat et al., 2023	The Solar System	3D Simulation	Mobile Augmented Reality (MAR)
8.	Rizki et al., 2023	Magnetic Field	3D Object	Adventuring Physics
9.	Ropawandi et al., 2022	Electricity (Static and Dynamic Electricity)	3D Simulation	AR application
10.	Sulisworo et al., 2021	Global Warming	3D Object	MBAR (Marker-Based Augmented Reality)
11.	Suprapto et al., 2020	Atomic Model	3D Object	PicsAR
12.	Suprapto et al., 2021	Planetary Motion	3D Object	Physics Pocketbook Based on Augmented Reality
13.	Thees et al., 2022	Electric Circuits	3D Object	HMD (Head-Mounted Display) - Microsoft HoloLens
14.	Wibowo, 2023	Concept of Ocean Physics	3D Simulation	Augmented Reality Integration (ARI)

The learning topics that most frequently utilize AR, particularly in physics learning, are presented in Figure 3 below.

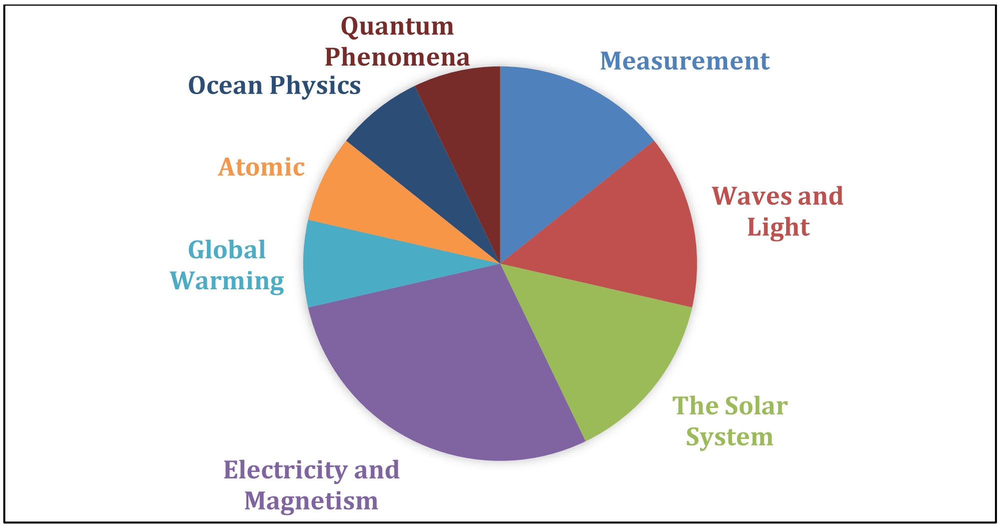

Figure 3. Trends in Physics Research Topics

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Table 4 and Figure 3 reveal that there are 4 studies focused on "Electricity and Magnetism," 2 studies on "Waves and Light," 2 on "The Solar System," 2 on "Measurement," and 1 study each on "Global Warming," "Atomic Model," "Quantum Phenomena," and "Ocean Physics." This data suggests that no studies in indexed scientific journals on Scopus have explored augmented reality applications in physics topics like "Mechanics," "Sound," "Fluids," "Heat," "Thermodynamics," "Relativity," or "Nuclear Physics and Radioactivity." As a result, developing AR media for these topics is recommended as a direction for future research. The types of AR used include 3D models, simulations, and videos.

Following this, VOSviewer was utilized to examine 46 documents on the application of augmented reality in science learning, sourced from the Scopus database. VOSviewer facilitated the visualization of a keyword map along with the connections between various keywords. This map also serves as a tool for spotting potential new research areas. The findings highlight several significant parameters and links between augmented reality and other variables. Keywords in titles and abstracts are represented by colored circles, with the size of each circle reflecting the frequency of studies on that topic. Larger circles signify more frequently appearing keywords. The mapping results from VOSviewer are illustrated in Figure 4.

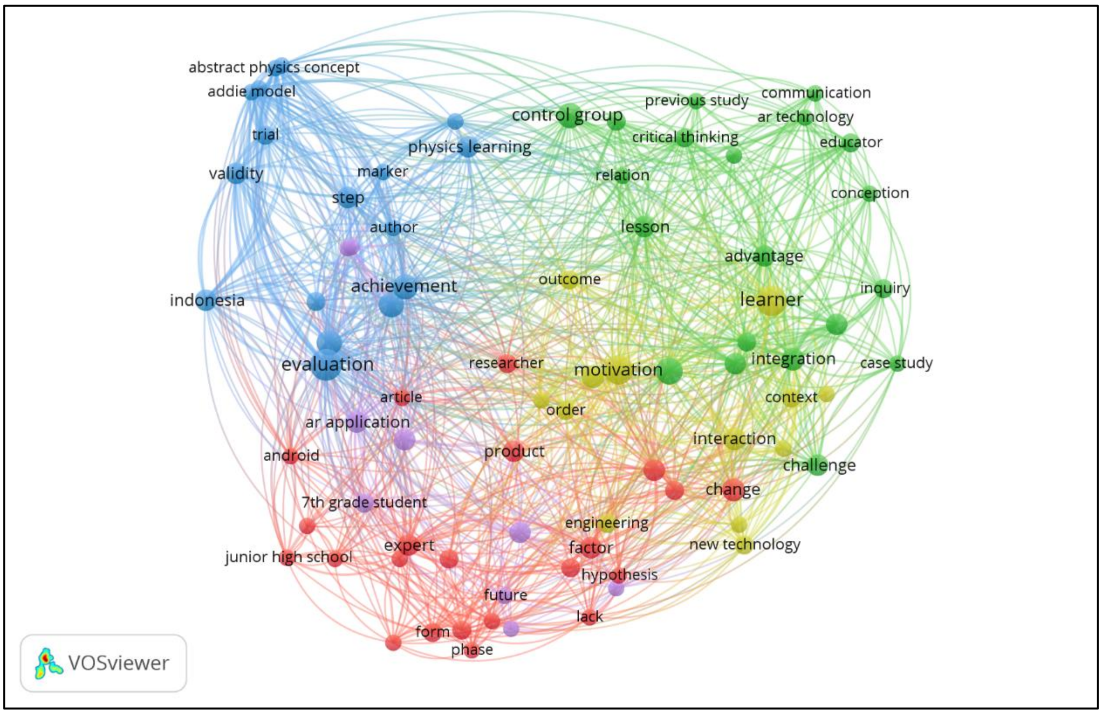

Figure 4. Trends in AR Research in Science Education According to Scopus Database

Figure 4 shows research trends in AR for science learning based on Scopus data from 2014 to 2023. The figure highlights five main clusters in AR research: AR technology (red), learning activities and 4C skills (yellow), AR development processes using the ADDIE model, including validity and research methods (blue), research variables (green), and AR applications in science learning (purple). Additionally, the connection between AR and critical thinking skills is illustrated in Figure 5.

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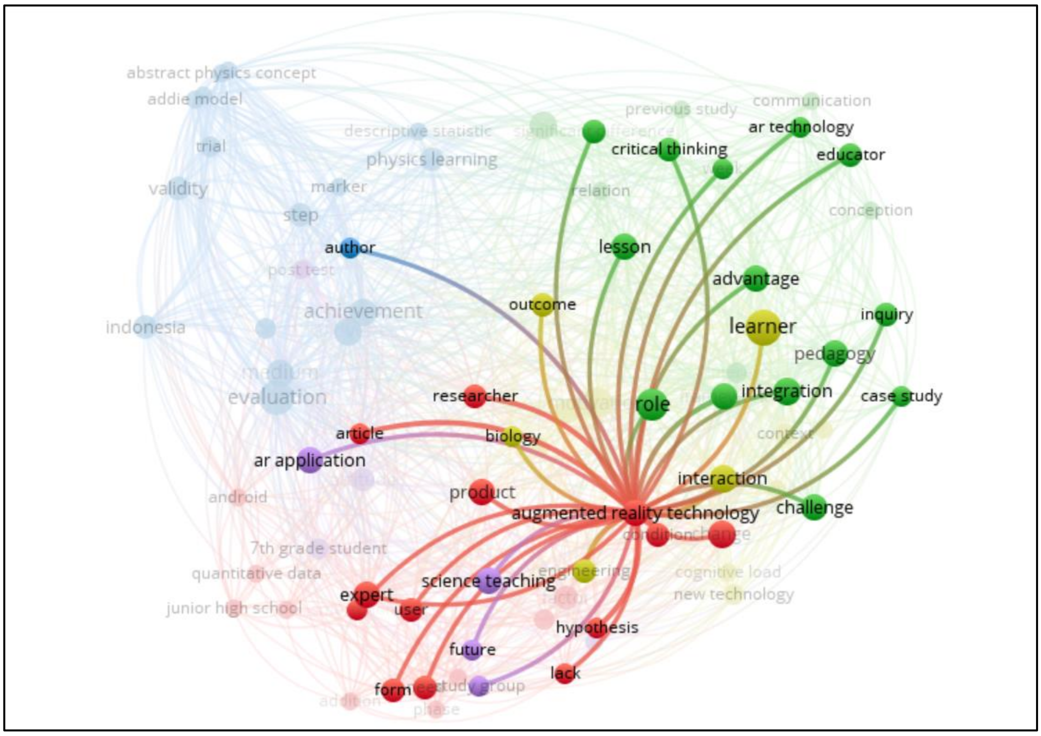

Figure 5. AR in Relating to Critical Thinking Skills

Figure 5 specifically illustrates how AR is related to critical thinking skills. It is evident that many researchers are exploring how AR can enhance students' critical thinking skills. However, among these studies, no research has been found that links augmented reality with multi-representation skills, which are essential in science education, especially in physics learning. Therefore, this study recommends future research on the impact of augmented reality on multi-representation skills.

DISCUSSION

The use of Augmented Reality (AR) in science learning has shown a significant positive impact on student learning outcomes. Research indicates that the integration of AR into the learning process not only enhances students' conceptual understanding but also strengthens critical thinking skills and collaboration abilities. For example, Fajari & Meilisa (2022) emphasize that AR-based learning media can improve students' critical thinking skills and digital literacy. Additionally, Qorimah & Sutama (2022) demonstrate that AR provides students with the opportunity to imagine, which in turn enhances their cognitive learning outcomes. This aligns with findings that AR can create a more dynamic and interactive learning experience, which is crucial in the context of 21st-century education.

One important aspect of using AR is its ability to enhance students' 4C skills (Critical Thinking, Communication, Collaboration, Creativity). Lai et al. (2018) note that AR-based learning approaches can increase student motivation, which contributes to the development of critical and creative thinking skills. Research by Marini et al. (2022) also shows that AR can enhance student engagement in learning, a key factor in achieving better learning outcomes. Therefore, the integration of AR in science education not only focuses on cognitive aspects but also on the development of students' social and emotional skills.

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This study has synthesized 46 articles discussing the use of AR in science education. The results of this study indicate that the use of AR in the learning process has a highly positive effect, particularly in strengthening students' critical thinking skills in science or physics learning (Syawaludin & Rintayati, 2019a; Damopolii et al., 2022; Thees et al., 2022; Alkhabra et al., 2023; Demircioglu et al., 2023; Wen et al., 2023; Wibowo, 2023). Learning activities or media that effectively support these skills include using comic media as AR markers in online learning (Damopolii et al., 2022), interactive AR-based multimedia (Syawaludin & Rintayati, 2019a), implementing an inquiry-based learning model with the QIMS framework using AR (Wen et al., 2023), applying AR-integrated Physics Independent Learning models (Wibowo, 2023), AR-based argumentation activities (Demircioglu et al., 2023), integrating AR for real-time data presentation in laboratory work (Thees et al., 2022), and the use of AR-based active learning approaches (Alkhabra et al., 2023).

Besides enhancing students' critical thinking skills in science learning, AR also supports students in deepening their conceptual understanding of the material being studied (Fleck & Hachet, 2016; Chiu et al., 2019; Bakri et al., 2020; Cai et al., 2021; Cai et al., 2022; Ropawandi et al., 2022; Tu et al., 2023), higher-order thinking skills (Sulisworo et al., 2021), abstract thinking abilities (Syawaludin & Rintayati, 2019b; Suprapto et al., 2020), academic achievement or success (Kirikkaya & Başgül, 2019; Lai et al., 2019; Özerbaş, 2019; Suprapto et al., 2021; Abdullah et al., 2022; Nasir & Fakhruddin, 2023; Rahmat et al., 2023), learning interest (Abdullah et al., 2022), and student motivation (Gopalan et al., 2015; Kirikkaya & Başgül, 2019; Lai et al., 2019; Gopalan et al., 2020; Czok et al., 2023a; Wibowo, 2023). In addition, AR aids in the development of science process skills (Abdullah et al., 2022), STEM literacy (Techakosit & Nilsook, 2016), argumentation skills (Demircioglu et al., 2023), self-efficacy (Cai et al., 2021; Chen, 2022; Krug et al., 2023), engagement (Gopalan et al., 2015; Czok et al., 2023a), creative thinking (Wen et al., 2023; Wibowo, 2023), collaboration and communication (Wibowo, 2023), and serves as a powerful tool for independent learning (Fleischer et al., 2023; Wen et al., 2023).

The integration of AR in the learning process is crucial, as supported by a preliminary study by Rejekiningsih et al. (2023), which highlighted students' need for AR-based learning tools. The results indicate that students are enthusiastic about using AR as a medium for learning science and have a positive outlook on its application in science learning (Karagozlu et al., 2019; Kececi et al., 2021; Krug et al., 2023). Generally, following the implementation of AR-based learning, students held favorable views, perceiving AR as a way to enhance motivation and interaction in science learning (Cheng, 2018). This aligns with findings by Karagozlu (2021), which show that AR in education helps students grasp science concepts more effectively, provides more engaging visualizations, and boosts interest and interaction in the classroom.

The study also underscores the positive effects of integrating various learning models into AR-based education on learning outcomes. For example, using the discovery learning model enhances students' conceptual understanding in physics (Bakri et al., 2020). The problem-based learning model has been shown to improve students' grasp of science topics (Karagozlu, 2021), while the inquiry-based learning model boosts conceptual understanding, student engagement, self-directed learning, creative thinking, critical thinking, and knowledge creation efficacy (Fleck & Hachet, 2016; Cai et al., 2022; Fleischer et al., 2023; Hsu et al., 2023; Wen et al., 2023). According to Kapp et al. (2022), inquiry-based learning in STEM labs enhances AR's role in simplifying complex visualizations in electrical experiments. Furthermore,

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approaches like game-based learning with gamification significantly increase student motivation and engagement, aiding students in visualizing abstract concepts in physics, such as magnetic fields (Rizki et al., 2023). Additionally, AR-integrated physics pocketbooks have been shown to support academic achievement improvements (Suprapto et al., 2021), while AR-based interactive multimedia promotes critical thinking (Syawaludin & Rintayati, 2019a). Consequently, incorporating AR in science education not only reduces cognitive load but also enhances student engagement and comprehension. By blending virtual elements with real-world settings, AR creates a dynamic and effective learning experience, fostering the critical thinking skills essential for 21st-century success.

Finally, it is important to note that although AR offers many benefits in science learning, its implementation must be carried out with caution. Research by Techakosit & Nilsook (2018) suggests that the use of AR should be well-designed to ensure that students can fully capitalize on this technology. Therefore, the learning process that integrates AR should involve a thorough analysis of students' needs and the learning context. With the right approach, AR can be a highly effective tool to enhance student learning outcomes, particularly in fostering critical thinking skills in science.

CONCLUSION

Based on the study review, it can be concluded that the use of AR has a positive impact on student learning outcomes in science learning. Integrating AR in science learning can enhance students' 4C skills, conceptual understanding, higher-order thinking skills, abstract thinking, academic achievement, learning interest, motivation, science process skills, STEM literacy, argumentative ability, self-efficacy, engagement, creative thinking, collaboration, and communication, as well as serve as a tool for independent learning. Integrating AR into the learning process creates a more dynamic and effective learning experience, ultimately fostering the critical thinking skills essential for 21st-century success. In the learning process, AR is presented through 3D objects, simulations, and videos. Physics topics enhanced through AR integration include electricity and magnetism, waves and light, the solar system, measurement, global warming, atomic models, quantum phenomena, and marine physics.

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