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RESEARCH ARTICLE

A Review Of Augmented Reality Implications And Challenges For Science Education: Current And Future Perspective

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ABSTRACT

This study systematically reviews the integration of Augmented Reality (AR) in science education, focusing on its trends, advantages, challenges, and practical applications. Over the past decade, AR has gained prominence as a tool for enhancing teaching and learning by visualizing complex and abstract scientific concepts. The review analyzed 47 studies published between 2013–2023, primarily sourced from Scopus, following PRISMA guidelines. The findings revealed a steady increase in AR-related research since 2017, with higher education being the most explored level, followed by primary and secondary education. Smartphones were identified as the most commonly used AR devices due to their accessibility and affordability. AR offers significant benefits, including improved student motivation, critical thinking, and academic performance, along with immersive and interactive learning experiences. It supports diverse pedagogical approaches, such as experiential, inquiry-based, and project-based learning, effectively addressing abstract topics in science education. Practical applications include AR-based anatomy lessons, molecule simulations, and virtual experiments, which make learning more engaging and accessible. Despite its advantages, challenges persist. These include technical difficulties, such as device incompatibility, cyber sickness, and high costs, as well as pedagogical barriers like limited teacher expertise and content availability. Addressing these issues requires investments in teacher training, adaptive AR interfaces, and the development of cost-effective and user-friendly systems. AR holds transformative potential for science education by fostering engagement and 21st-century skills. However, its implementation must consider technical, cognitive, and institutional challenges. Future research should explore innovative solutions to enhance usability, reduce costs, and expand AR's integration into various educational contexts, ensuring sustainable and impactful adoption. The study underscores AR's role in bridging gaps in traditional science education, promoting 21st-century skills like critical thinking and problem-solving. It highlights the need for interdisciplinary collaboration in AR development and emphasizes the importance of evidence-based strategies for sustainable integration in educational practices.

INTRODUCTION

The rapid advancement of digital technologies has transformed the educational landscape, offering innovative solutions to traditional teaching challenges. One such innovation, Augmented Reality (AR), has emerged as a powerful tool in education, particularly in the sciences. By overlaying virtual elements onto real-world settings, AR creates immersive learning environments that enhance students' understanding of abstract and complex concepts. This technology bridges the gap between theoretical knowledge and practical application, fostering deeper engagement and critical thinking among learners. As educational demands evolve to meet the needs of the 21st century, there is a growing interest in leveraging AR to address persistent challenges in science education. Abstract scientific phenomena, often difficult to visualize through conventional methods, can now be brought to life through interactive AR experiences. This potential makes AR a promising avenue for transforming the learning process, improving student outcomes, and preparing them for future challenges in a rapidly changing world.

AR is a transformative technology that enhances real-world environments by overlaying digital content such as images, animations, or sounds, offering a unique blend of physical and virtual interaction. Unlike Virtual Reality (VR), which immerses users entirely in a simulated environment, AR bridges the gap between the real and digital worlds, enabling learners to interact with virtual elements while remaining engaged with their physical surroundings. This feature makes AR particularly relevant in education, where it can simplify complex concepts like molecular structures, microscopic organisms, and physical phenomena. By providing an immersive and interactive learning experience, AR fosters deeper understanding, engagement, and motivation among students, making it a powerful tool for modern education (Cabero-Almenara et al., 2019; Yapici & Karakoyun, 2021). However, challenges such as cost, accessibility, and teacher training remain critical barriers to widespread adoption (Perifanou et al., 2023). Addressing these challenges through strategic investments and training programs can unlock AR's full potential in elevating educational outcomes.

AR Technology is increasingly widespread and in demand in the education sector. There is a current demand for AR in science education due to its effectiveness in aiding the comprehension of complex abstract concepts such as molecular structures, microscopic objects, and physical phenomena (Arici et al., 2019). Several studies have explored the use of AR in the classroom, including its impact on students' attitudes toward science (Sahin & Yilmaz, 2020), learning (Petrov & Atanasova, 2020), and student engagement (Wang, 2022). Over the last decade (2012-2022), systematic literature review research has indicated the influence and benefits of AR in learning (H.-Y. Chang et al., 2022). Despite its potential, there are challenges associated with integrating AR into science education. AR creation tools are costly (Dengel et al., 2022), and teachers may need the necessary skills to effectively utilize AR in the classroom (Perifanou et al., 2023). Therefore, this study aims to identify the shortcomings and limitations of the current literature. Conducting a comprehensive review of the existing literature is crucial to consolidate knowledge about what works and what does not and the next steps for optimizing the integration process.

Using AR as a teaching aid has the potential to enhance student learning significantly. AR has been proven to be effective in various fields, including science (Cabero-Almenara et al., 2019), biology (Yapici & Karakoyun, 2021), and mathematics (Chen et al., 2017). The incorporation of learning strategies can enhance the effectiveness of learning through AR. This is consistent with findings showing that learning using AR combined with learning strategies can enhance the quality of learning (Hanid et al., 2020a). The educational value of AR is evident not only in the use of technology but also in the integration and development of AR in formal and informal learning settings.

The benefits of AR in learning have been documented, demonstrating its numerous advantages in education. Previous studies have employed various methods across different levels of education and subject domains, such as game-based learning approaches (Alper et al., 2021), AR in online learning

(Saefurohman et al., 2021), and a review of AR in STEM (Mystakidis et al., 2021). A review of AR in education from 2000–2013 identified 32 high-quality empirical studies (Bacca et al., 2015). No publication has reviewed AR in science education from 2013 to 2023 based on the study above. While there is some research on AR in education, review studies are still necessary. This research encompasses trends in AR studies, specifically focusing on science education. Additionally, we examined AR devices, research methods, distribution at the educational level, advantages of using AR, challenges, learning methods, and practical applications in science education.

This review examines the implications and challenges of integrating AR into science education, exploring current applications and future perspectives. The results of this study can influence education policy by promoting the implementation of AR through adequate resources, training, and technological infrastructure. These systematic literature reviews can provide developers valuable insights into educational technology, enabling them to create user-friendly and cost-effective AR systems. Consequently, this will encourage and drive further advancements in science education. In summary, this systematic literature review will elevate the standard of science education by offering a more engaging and participatory learning approach. Overall, this systematic literature review will enhance the quality of science education by providing a more engaging and interactive approach to learning, thereby strengthening science literacy among students and preparing them for future challenges.

AR holds immense potential to address persistent challenges in science education by making abstract and complex concepts more tangible and engaging for students. By overlaying interactive digital content onto real-world environments, AR enhances visualization and promotes active learning, helping students grasp difficult subjects like molecular structures or physical phenomena. This technology fosters deeper understanding, motivation, and critical thinking, ultimately leading to improved academic outcomes. As an innovative tool, AR not only bridges the gap between theory and practice but also prepares students to meet the demands of a rapidly evolving, technology-driven world.The present study aims to guide this literature review by addressing the following research questions:

RQ1: What is the trend of AR studies in science education?;

RQ2: What are the advantages of using AR in science education?;

RQ3: What are the challenges of integrating AR in science education?;

RQ4: What are the relevant AR learning methods and their practical applications in science education?"

METHODOLOGY

This study employs a systematic review methodology to explore the utilization of AR in science education. This study employs a systematic literature review (SLR) methodology, guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, to explore the utilization of Augmented Reality (AR) in science education. The review process involves identifying, evaluating, and analyzing the most recent and relevant information from the literature to comprehensively address research questions (Xiao & Watson, 2019). The systematic review aims to methodically and transparently summarize the latest findings and address research questions (Kurniati et al., 2022).

Data Collection

The data search was carried out using Scopus, the world's largest and highly reputable journal database, which yielded 248 articles related to AR in education from 2013 to 2023 (out of a total of 516 results for all years). We focused on empirical studies and theoretical articles discussing the implementation of AR in teaching. The evaluated articles included journals published between January 2013 and December 2023, using the keyword "augmented AND reality AND in AND education." From the initial 516 articles found, we narrowed the search by categorizing papers relevant to the social sciences, resulting in 248 articles. Further refinement focused only on scientific articles, excluding reviews, letters to editors, editorials, book reviews, and brief reports, resulting in 146 articles. The final selection was limited to articles published in English and open access, resulting in 63 articles, and eventually filtered down to 47 articles relevant to science education. We excluded systematic articles, coverage reviews, and meta-analyses.

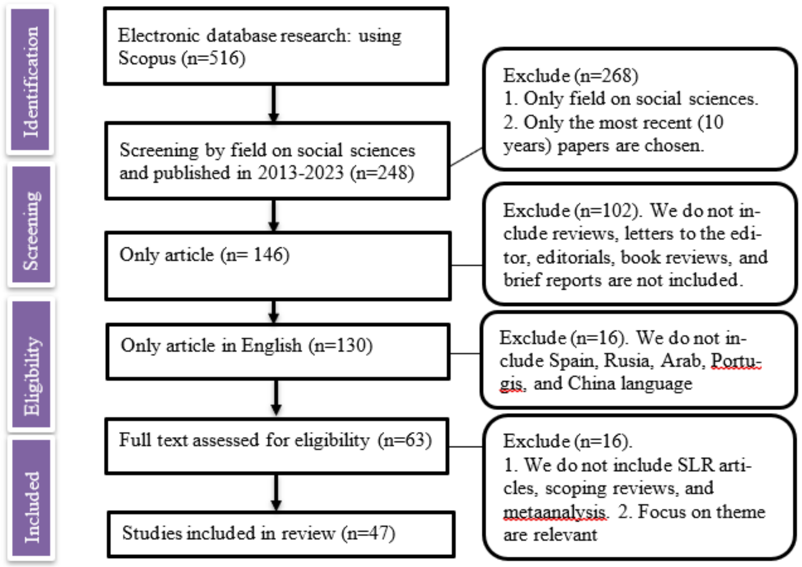

Figure 1. Literature selection process using PRISMA Diagram

Data Analysis

The selected study is based on the inclusion and exclusion criteria established using the PRISMA model (Moher et al., 2015). The data obtained is stored in CSV and RIS formats and then organized using Reference Manager (Mendeley). The search in Scopus uses a combination of the keyword "TITLE (augmented AND reality AND in AND education)" with restrictions on the subject "Soci" (social sciences), article document type, English, and open access articles.

Results

We examined trends in the application of AR in science education to provide detailed information, based on a review of studies on the subject. The trend analysis concentrates on the distribution of years, research methods, tools, educational levels, and educational fields that utilize AR.

Distribution of year

Over the past decade, the search results have yielded numerous significant insights. Through the analysis of articles published over this timeframe, researchers were able to discern emerging patterns and quantify the volume of publications in the respective subject. Hence, search results play a crucial role as a fundamental basis for subsequent research and advancement in this dynamic and swiftly growing area of study. This rise in publication has made the topic of AR publication in science education popular. Figure 2 shows the number of articles on AR in science education published between 2013 and 2023.

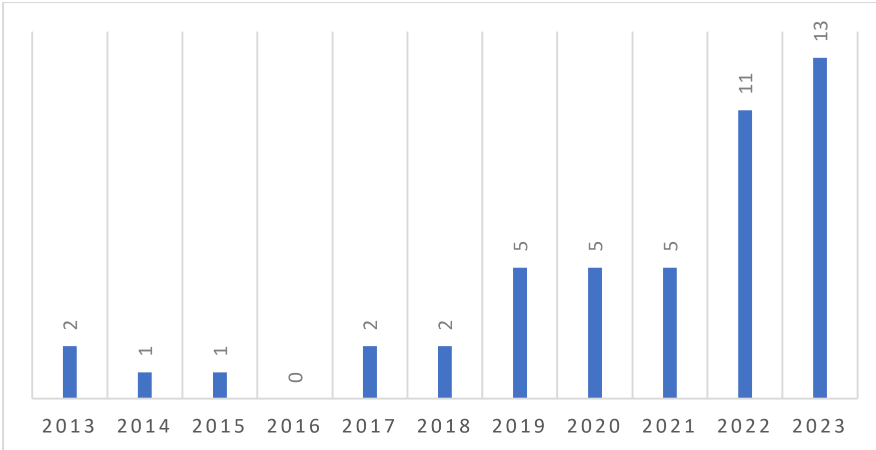

Figure 2. Article distribution by year

RESEARCH METHOD

Figure 3 displays the latest developments in research on education that is centred around expanded reality. The results suggest that the application of AR in science education is mostly investigated using quantitative research methodologies. Quantitative methodologies allow for the utilisation of impartial measurements and results that may be extrapolated to a broader population. Researchers employ statistical data to derive insights that reveal patterns applicable in a broader context. The results align with Fidan & Tuncel (2019), which involved 91 seventh grade students to ensure generalizability to a broader population.

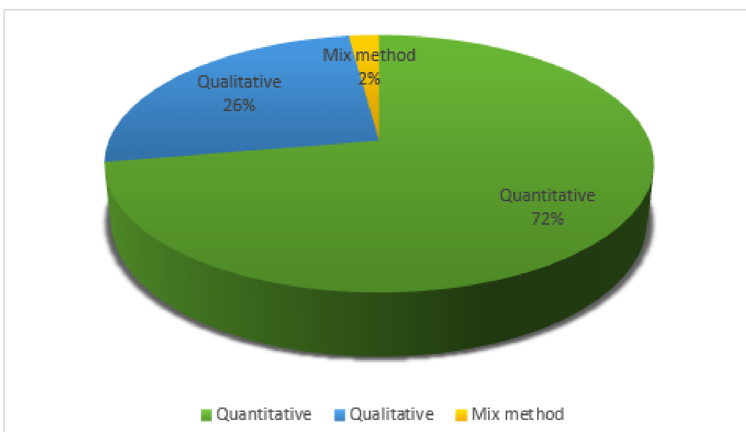

Figure 3. Research method

The most widely used device in AR learning

The use of device in AR mostly uses smartphones (f=26), next is a tablet (f=6), followed by the use of tools using AR books (f=3), Hololens (f=3), VR headsets and smartglasses. The analysis reveals that the smartphone is the most widely used tool in AR-based learning. Table 1 shows the use of device in the AR.

Table 1. Distribution device of using AR

No	Devices	f	Sample References
1	Smartphone	26	(Wang et al., 2013)
2	Tablet/smartphone	6	(Mayilyan, 2019)
3	AR Book	3	(Jafari, 2023)
4	iPad	3	(Chen et al., 2023)
5	HoloLens	1	(Moro et al., 2021)
6	Tablet/smartphone/windows	1	(Rodríguez et al., 2021b)
7	VR Headset/smartphone	1	(Huang et al., 2019)
8	Smartglass	1	(Kapp et al., 2022)
9	Google glass	1	(Kamphuis et al., 2014)
10	AR sandbox (ARS)	1	(Baumann & Arthurs, 2023)
11	Head-mounted display (HMD)	1	(Schoeb et al., 2020)
12	Eye-Tracking Device	1	(Jafari, 2023)
13	AR headset	1	(Donovan, 2023)

Education levels

The most significant proportion was in higher education (f=12), followed by primary (f=10), medical education (f=7) and other education levels such as health care education, pharmacy education, vocational, informal education, and preschool teacher, as shown in Table 2. The analysis showed that AR was carried out at all grade levels. Our search findings showed that AR has primarily been used in higher education (at the undergraduate level or equivalent) and compulsory education (including primary, lower secondary, and upper secondary education).

Table 2. AR distribution AR in education levels

No	Education Level	f	Sample Research
1	Higher education	12	(Stojšić et al., 2018)
2	Primary school	10	(Baran et al., 2020)
3	Medical Education	7	(Schoeb et al., 2020)
4	Secondary school	4	(Velázquez & Méndez, 2018)
5	Middle school	3	(AlNajdi, 2022)
6	Science teacher	3	(Marín-Díaz et al., 2022a)
7	Informal science learning	2	(Salmi et al., 2017)
8	Health care education	1	(Zhu et al., 2015)
9	Pharmacy Education	1	(Kapp et al., 2022)
10	Vocational	1	(Bacca et al., 2019)
11	Vocational and higher education	1	(Zuhairy et al., 2021)
12	Preschool teacher	1	(Sofianidis, 2022)
13	Preservice teacher	1	(Krug et al., 2023a)

The fields of science education

AR use in educational environments has recently become a popular research topic. Natural sciences became the most researched subject, followed by health care/medical education, and others. Figure 4 shows that the majority of research took place in the field of science education. Our results show that one of the less explored areas of science education is biology (Figure 4). These results are important to encourage researchers to explore the use of AR in various educational fields.

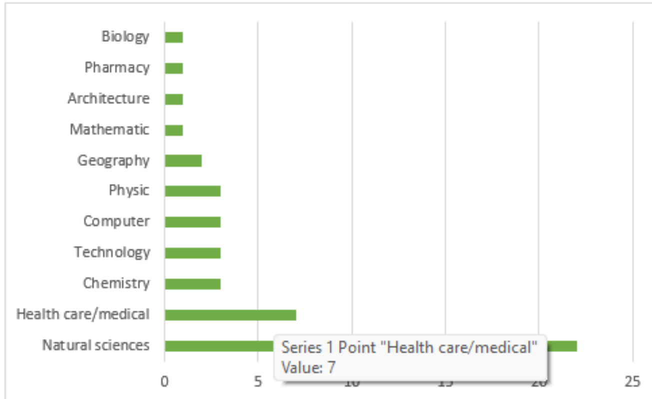

Figure 4. The fields of science education

The advantages of using AR in science education

Table 3 shows the advantages of using AR in science education. The AR was then aggregated into five categories: increase motivation and attitude, increase performance and self-efficacy, cognitive aspects and critical thinking, 21st century skills, an enjoy full and immersive learning experience. These results show that the subject of AR in science education provides enhanced cognitive aspects by making abstract concepts easier to learn and thus the basis for developing 21st-century skills through enjoyable learning.

Table 3. Advantages of using AR in science education

Categories	Subcategories	f	Sample Research
Increase motivation and attitude	Motivation	7	(Salmi et al., 2017)
	Attitude toward application	2	(Stojšić et al., 2018)
	Attitude toward use	2	(Su, 2019)
	Attitude toward science	1	(Çetin & Türkan, 2022)
Increase performance and self-efficacy	Student performance	5	(Wang et al., 2013)
	Self-efficacy	2	(Krug et al., 2023a)
Cognitive aspects and critical thinking	Avoid misconceptions	2	(Baumann & Arthurs, 2023)
	Critical thinking	1	(Demircioglu et al., 2022)
	Cognitive aspects	1	(Huang et al., 2019)
21st century skills development	21st century skills	1	(Wen et al., 2023b)
An enjoyfull and immersive learning experience	Immersiveness of the experience	14	(Kerr & Lawson, 2020)
	Visulization	4	(González & Marrero, 2023)
	Fun learning	3	(Marín-Díaz et al., 2022a)
	Teach abstract concepts	2	(Nadeem et al., 2022)

Challenges hinder the integration of AR in science education

Although articles on the use of AR in science education highlight the positive contributions, some challenges related to its use were emphasized in Table 4. We found challenges in AR learning divided into five categories: technical and device difficulties, learning and pedagogical issues, facility and cost limits, user experience issues, and the challenge of creating a mixed learning environment.

Table 4. Challenges of using AR in science education

Categories	Sub Categoris	f	Sample Research
Technical and devices difficulties	Lack of availability of AR support devices	2	(Velázquez & Méndez, 2018)
	Technical issues (broken images/animation/connections)	2	(Sofianidis, 2022)
	Applications are running slowly	2	(Silva, et al., 2023)
	Device not supported	1	(Nordin, Nordin, et al., 2022)
	Uncomfortable, heavy HMDs, short battery life, complicated handling	1	(Schoeb et al., 2020)
	Applications for paid iPhones are not free	1	(Donovan, 2023)
	Uncomfortable using smart glasses	1	(Kapp et al., 2022)
Learning and pedagogical issues	Lack of teacher expertise in design, techniques, and theory	6	(Kerr & Lawson, 2020)
	Deficiency in adapting design concepts to the lessons	3	(Bacca et al., 2019)
	Lack of teachers and students' ability to adapt to new technologies	2	(Nadeem et al., 2022)
	No established process for building an AR framework	1	(Zhu et al., 2015)
	AR integration in the classroom is ineffective	1	(Salmi et al., 2017)
	Pedagogical issues in developing AR for learning environments	1	(Jafari, 2023)
Facility and cost limits	Expensive cost/Lack of free content	4	(Rodríguez et al., 2021b)
	The availability of resources for creating interactive media products in schools is still limited.	2	(Rejekiningsih et al., 2023b)
User experience issues	Cybersickness	2	(Moro et al., 2021)
	Cognitive load	1	(Chen et al., 2023)
	Spend much more time	2	(Baumann & Arthurs, 2023)
	Weak cognitive and psychological responses	1	(Huang et al., 2019)

	Lack of engagement	1	(Nadeem et al., 2020)
	Restricted views of the shared virtual environment	1	(Baran et al., 2020)
The challenge of creating a mixed learning environment	Creating a mixed-reality learning environment that combines the virtual and physical worlds must be targeted	1	(Lampropoulos et al., 2023)
	Not Mention	8	(Campos et al., 2022)

Learning methods and practical application using AR in science education

The concept of AR in science education reflects the essential integration of pedagogical elements with learning experiences. Understanding and using AR has a huge impact on creating meaningful and efficient learning. Table 5-11 shows the different learning strategies and models used in different types of AR and gives different practical applications at different levels of education. This technique directly investigates concepts and generates meaning through active exploration, thoughtful observation, abstract conceptualization, and practical learning. Table 5 shows characters in practical application using AR at the primary education level. The primary education level uses a variety of learning methods, consisting of project-based learning, experiential learning, online learning, and inquiry-based learning. This level uses AR to visualize basic concepts.

Table 5. The primary education levels utilize AR methods and practical applications

Name of AR	Learning Method	Practical Application
AR globe (Mayilyan, 2019)	Project-based learning	Using AR tends to be simpler by visualizing basic concepts in learning, like geometry in mathematics and science. Interactions with AR are more intuitive, with the aim of reinforcing the fundamental concepts.
AR app (Setiawan et al., 2023)	Project-based learning	
Arcoo Software (Jafari, 2023)	Project-based learning	
Electric vehicle AR (Çetin & Türkan, 2022)	Online learning	
AR "senses" (Abdullah et al., 2022)	Experiential learning	
AR of medieval knight's armor (Jeřábek et al., 2013)	Experiential learning	
AR (Baran et al., 2020)	Experiential learning	
AR and VR geometry (Demitriadou et al., 2020)	Experiential learning	
AR app (Fearn & Hook, 2023)	Experiential learning	
The Plant Lifecycle (Wen et al., 2023b)	Inquiry-based learning	

Note. Project based learning and experiential learning are the most learning method in primary school.

Table 6 shows characters in practical application using AR at the middle school. The middle level uses experiential learning and project-based learning. This level employs AR to present concepts in a more advanced manner compared to the primary school level.

Table 6. The middle school levels utilize AR methods and practical applications

Name of AR	Learning Method	Practical Application
QR codes and iEN (AlNajdi, 2022)	Experiential learning	AR is employed to facilitate additional learning. The AR application offers interactive simulations and immersive experiences. The level of complexity is higher than in primary school, with more complex concept integration.
Android-based AR (Rejekiningsih et al., 2023b)	Project-based learning	
AR app Astronomy (Demircioglu et al., 2022)	Project-based learning	

Note. Project based learning is the most learning method in middle school.

Table 7 shows characters in practical application using AR at the secondary school. The secondary education level uses experiential learning, online learning, problem-based learning, and STEM. This level employs AR to visually represent more precise topics, such as exploring physiological processes in biology lesson.

Table 7. The secondary levels utilize AR methods and practical applications

Name of AR	Learning Method	Practical Application
AR and mobile devices (Velázquez & Méndez, 2018)	Experiential learning	Specialized subjects like biology, physics, and technology utilize AR more deeply. AR applications can provide a more realistic and detailed learning experience, like the digestive system. Students work independently to explore complex concepts using AR.
Mobile AR (Stojšić et al., 2022)	Online learning	
FenAR (Fidan, 2019)	Problem-based learning	
GAR-STEM (Su, 2019)	STEM	

Note. A variety of learning methods (experiential learning, online learning, problem-based learning, STEM) at the secondary level.

Table 8 shows characters in practical application using AR at higher education. The higher education level uses a variety of learning methods, consisting of experiential learning, game-based learning, online learning, virtual laboratory, and STEM. This level of AR uses more advanced technology to study material in greater depth.

Table 8. The higher education and vocational educations levels utilize AR methods and practical applications

Name of AR	Learning Method	Practical Application
AR/VR solar system (Huang et al., 2019)	Experiential learning	Research, development, and practical applications in disciplines like chemistry, architecture, and technology utilize AR. AR applications in colleges involve the development of more advanced technologies (AR/VR headser, Smartglas, ARS), such as building structural engineering or creating works. Practical application and in-
Master of Time (Kerr & Lawson, 2020)	Experiential learning	
MoleculARweb (Rodríguez et al., 2021b)	Experiential learning	
4R4FSM (Nadeem et al., 2022)	Experiential learning	
Augmented Reality app (Silva, Monica, Bermúdez & Caro, 2023)	Experiential learning	

AR mobile or desktop (Bacca et al., 2019)	Experiential learning	depth research with high levels of complexity often drive its use.
Voltrent AR (Zuhairy et al., 2021)	Experiential learning	
REV-OPOLY (Nordin, Nordin, et al., 2022)	Game-based learning	
The ARICE (Wang et al., 2013)	Game-based learning	
GEQ in-game module (Lampropoulos et al., 2023)	Game-based learning	
AR in sport science (Campos et al., 2022)	Online learning	
AR-LaBOR (Nadeem et al., 2020)	Virtual laboratory	
MAR apps (Stojšić et al., 2018)	STEM	
Map-Reading (Baumann & Arthurs, 2023)	STEM	

Note. Experiential learning and STEM are the most learning method at the higher and vocational level.

Table 9 shows characters in practical application using AR at health care, medical, and pharmacy education. The health care, medical, and pharmacy education level uses a variety of learning methods, consisting of experiential learning, game-based learning, online learning, project-based learning, and virtual laboratory. This level of AR employs object visualization to imitate surgical procedures, aiding students in comprehending the intricacies of human anatomy.

Table 9. The health care/medical education/pharmacy levels utilize AR methods and practical applications

Name of AR	Learning Method	Practical Application
MARE (Zhu et al., 2015)	Experiential learning	Medical students can practice without risk to patients by using AR to simulate surgical procedures or simulate laboratory procedure, such as determine an antimicrobial substance's MIC (minimum barrier concentration) for the tested bacteria. AR facilitates anatomical learning by allowing students to see and manipulate the structure of the human body in 3D, helping them gain a deeper understanding. Medical students can practice handling a variety of emergency medical situations in a secure and controlled virtual environment through the use of AR in clinical training scenarios.
Mix reality catheter (Schoeb et al., 2020)	Experiential learning	
AR skull anatomy (Moro et al., 2017)	Experiential learning	
AR brain (Moro et al., 2021)	Experiential learning	
Human anatomical structure (Kamphuis et al., 2014)	Experiential learning	
AR into board games (Lin et al., 2021)	Game-based learning	
HeARt app (Christopoulos et al., 2021)	Online learning	
ARI-MBS (Donovan, 2023)	Project-based learning	
AR (Kapp et al., 2022)	Virtual laboratory	

Note. Experiential learning is the most learning method at the medical education.

Table 10 shows characters in practical application using AR at informal education. The informal education level uses project-based learning and experiential learning. At this stage, the focus of AR is on self-directed learning through the study of science, technology, or other subjects.

Table 10. The informal education levels utilize AR methods and practical applications

Name of AR	Learning Method	Practical Application
AR in museum (Chen et al., 2023)	Project-based learning	AR can provide learning that is highly contextual and relevant to individual needs, such as thermal motion simulations in natural science.
AR exhibits (Salmi et al., 2017)	Experiential learning	

Note. Project-based learning and experiential learning are learning method at informal education.

Table 11 shows characters in practical application using AR at preschool teacher, preservice teacher, and science teacher. The preschool, preservice, and science teacher education level uses a variety of learning methods, consisting of experiential learning, project-based learning, and STEM. Prospective teachers use AR to create learning that can enhance student motivation. The curriculum emphasizes the fundamental structure of AR development.

Table 11. The preschool teacher, preservice teacher, and science teacher levels utilize AR methods and practical applications

Name of AR	Learning Method	Practical Application
AR quizzes (Sofianidis, 2022)	Experiential learning	AR increases the motivation and involvement by making learning more interesting and enjoyable. The curriculum adapts the learning framework to align with the learning objectives. AR supports independent and collaborative learning, enabling teachers and prospective teachers to study independently or collaboratively in an interactive environment.
Mobile device AR (Marín-Díaz et al., 2022)	Experiential learning	
AR app (González-Pérez & Marrero-Galván, 2023)	Project-based learning	
AR in science course (Ateş & Garzón, 2023)	Project-based learning	
AR (Krug et al., 2023a)	STEM	

Note. Project-based learning and experiential learning are the most learning method in the preschool teacher.

DISCUSSION AND CONCLUSION

Our findings show a significant increase in AR-related publication activity since 2017, with a sharp spike in 2019 and peaking in 2022. This trend is consistent with previous research that found an increase in the use of AR in education, especially after the COVID-19 pandemic (Irwanto et al., 2022). Other findings also reveal an increasing trend of AR in education in 2019 (Garzón, 2021). Furthermore, there was a significant publication surge after the COVID-19 pandemic in 2022-2023. Scientific research in education, especially science education, is increasingly focusing on AR due to its direct influence on digital technology. Educators and policymakers should be aware of the potential of AR in science education. There is an interest in incorporating innovative technological devices to create a more engaging and interactive learning experience.

Researchers continue to support quantitative methods in AR research in science education, mainly because they can provide objective measurements and results that can be applied to a broader population. This aligns with previous research that emphasizes the importance of quantitative methods in evaluating the effectiveness of educational technologies such as AR. For example, research by Nordin et al. (Nordin, Mohd Nordin, et al., 2022) shows that a quantitative approach can provide reliable results in measuring the impact of AR on students' academic performance and attitudes. In addition, using quantitative methods also supports research that aims to capture critical trends in the use of AR at different levels of education. However, these findings also challenge some previous studies by pointing out the limitations of quantitative methods in exploring the context and processes underlying the research results. Quantitative approaches cannot need or explore how AR affects student interactions and learning experiences holistically. Therefore, there is an increasingly urgent need to adopt a blended method approach that combines qualitative and quantitative elements to provide a more comprehensive understanding of the use of AR in education.

The most widely used device in learning is a smartphone or tablet. Smartphones and tablets are the most reliable devices for AR in education because they are affordable. The smartphone can see or identify the subject the camera focuses on. Physical markers, such as quick response (QR) codes, positioned on items within the environment allow AR systems to rely on them. Smartphones serve as standout AR illustrations. Specific systems use special glasses or goggles to present information visually. In line with the results of our analysis of the findings, the tools for using AR are not only smartphones, but smartphones are the most dominant. Everyone today has a smartphone (Corrocher & Zirulia, 2009); therefore, smartphones are more widely used in AR learning. Easily accessible smartphones allow for broader integration of AR in various learning environments, thereby increasing student engagement and facilitating understanding of complex concepts. This shows that the choice of device is not only about the frequency of use but also the impact on the quality of the student learning experience.

AR learning has been shown to improve students' motivation, attitudes, and critical thinking skills and help them understand abstract material that is difficult to explain in a traditional environment. AR is a technology that answers the challenges of the 21st century (Kamińska et al., 2023). One of the must-have skills in the 21st century is critical thinking. Several studies have revealed that AR learning can improve critical thinking skills (Alkhabra et al., 2023; Badriyah et al., 2023).

In addition to the benefits of AR learning, there are challenges. Challenges in AR learning include device accessibility issues, limited educational content, and the risk of cybersickness and cognitive overload, all of which must be considered in the future development of AR. Challenges such as cybersickness and cognitive load are crucial in future AR development as they can hinder learning and user experience effectiveness. Cybersickness, which is often characterized by symptoms such as nausea and dizziness, can reduce students' comfort and engagement in using AR technology. Meanwhile, cognitive load can confuse students, interfere with comprehension, and decrease learning effectiveness. To address these challenges, developers can consider solutions such as designing a more user-friendly and intuitive interface, testing and customizing AR content extensively and implementing cognitive load reduction techniques, such as simplifying visual information and using clear physical markers. By addressing and understanding these challenges, future AR development can be more effective in enhancing students' learning experiences without sacrificing comfort and understanding.

Our finding is that other AR learning difficulties take a lot of time. Students spend more time researching specific hypotheses through 3D animation, and the visual features provided by AR require more work to project. A lot of time, money, and effort may be required for this procedure, as well as the help of an experienced instructor with established courses and other responsibilities (Sarigoz, 2019). According to a literature review study by Alzahrani (Alzahrani, 2020), the lack of teacher preparation is the cause of difficulties in learning AR.

The first learning method in the creation of AR is experiential learning. Experiential learning requires active participation and involvement in learning (Morris, 2019). The core of the learning process is around student participation, with the basic principle of learning through practice (Munge et al., 2018). An experiential learning approach can make it easier for students to understand the subject

(Falloon, 2020). Our findings suggest that AR in STEM can positively impact attitudes (Luque et al., 2022). AR learning through games can provide a valuable experience for students and enhance the context of learning through authentic experiences in natural spaces (Kwon et al., 2015). A systematic literature review of this study reveals that game-based learning has many benefits for biology learning (Situmorang et al., 2024). Another learning method is project-based learning. Project-based learning is a long-term inquiry driven by real questions connected to the real world, resulting in authentic products demonstrating student learning (Wolk, 2022).

Furthermore, inquiry-based learning is an educational approach in which students use procedures and practices similar to those of professional scientists to build their knowledge. One of the main reasons is that its success can be significantly enhanced by the latest technological advances that facilitate the inquiry process through electronic learning environments (Pedaste et al., 2015). An inquiry approach can improve students' knowledge of biology and develop their critical thinking skills (Suwono et al., 2022). In line with our findings, inquiry-based learning combined with AR technology improves 21st-century skills. Another learning method we found was combining PBL with AR in physics. Case-based learning can improve critical thinking skills (Suwono et al., 2017). AR gives students an illustration of the phenomenon. Teachers become facilitators in the learning process, allowing students to make decisions (Suwono et al., 2021). This review of research reveals that the AR learning approach can be done using online or blended learning. During the pandemic, learning was carried out online (Ramlo, 2021). Blended learning delivery modes can improve learning, including AR, digital tools, or platforms with human-to-machine interaction capabilities (Castro, 2019).

Our findings reveal that AR has different practical applications at each level of education. When using AR in the classroom, practical applications must adapt to the age and complexity of the material (Dunleavy, 2009). The application of AR in education spans a wide range of levels, from primary school to higher education, with a focus on understanding complex materials and developing analytical skills. AR implementations in elementary schools often involve apps and devices designed to help students understand the material through engaging 3D visualizations. For example, a simple application of plant identification, planets, or anatomy sections can help students better understand the subject they are studying. At the junior and senior secondary levels, learning focuses on the depth of academic material and developing analytical and critical skills. For example, space exploration with 3D models can make learning more immersive and interactive. At the higher education level, learning is focused on research, specialist skill development, and interdisciplinary collaboration. Higher education can use AR for medical simulations and various other research applications. For example, virtual surgical exercises with AR allow medical students to practice without risk to patients. Additionally, environmental data analysis with 3D models can provide a better understanding of natural phenomena.

This analysis reveals that publication trends, advantages, and challenges in AR can influence teachers' attitudes and beliefs to integrate AR into science education, as shown in the following example Marín-Díaz et al. (Marín-Díaz et al., 2022b) found based on the results of a survey on teachers' visions that teachers need AR training for teachers' professional development. Other research also revealed that AR-related teacher training can respond to the demand of teachers in the 21st century to use technology in learning (González-Pérez & Marrero-Galván, 2023). This analysis reveals that publication trends, advantages, and challenges in AR can influence teachers' attitudes and beliefs to integrate AR into science education, as shown in the following example Marín-Díaz et al. (Marín-Díaz et al., 2022b) found based on the results of a survey on teachers' visions that teachers need AR training for teachers' professional development. Other research also revealed that AR-related teacher training can respond to the demand of teachers in the 21st century to use technology in learning (González-Pérez & Marrero-Galván, 2023). The DiKoLAN framework used for seminars or training can help aspiring teachers in science classes improve their self-efficacy and attitudes towards AR (Krug et al., 2023). In addition to teacher training, securing stakeholder support is critical. One study we found through this analysis revealed that school support is essential for developing professional teachers (Fearn & Hook, 2023).

The objectives of this study have been successfully achieved, demonstrating the significant impact and broad potential of AR in science education. The surge in scientific output over the past decade underscores the growing interest and relevance in this field. However, some challenges have been identified, which must be addressed in future research to improve the effectiveness of AR. Future research may explore adaptive interface designs that adjust the level of complexity based on students' abilities or investigate visual techniques to reduce cybersickness symptoms. These findings suggest that AR educators and developers should consider students' physical comfort and cognitive capacity, with teachers receiving specialized training to recognize and manage cognitive load or cyber sickness. Although comprehensive, this systematic review has limitations as it relies on only Scopus-indexed publications from 2013 to 2023 and English-language papers. Future research should consider exploring additional databases to expand the scope and findings.

Limitations and Implementations

Furthermore, despite this thorough research, every systematic review has limitations due to its criteria. This systematic literature review was not fully exhaustive due to the restricted search parameters, which only included publications indexed by Scopus from 2013 to 2023 and papers written exclusively in English. Additional investigation is required on alternative databases that could be advantageous due to their ability to facilitate the completion of assigned activities easily. The selection is directly contingent upon the objectives the researcher aims to accomplish.

Author contributions

Arinda Eka Lidiastuti: writing-review & editing, interpretation of data, formal analysis, and substantially revised. Hadi Suwono: conceptualization, review & editing, formal analysis and susbtantially Nurul Asikin: search data & editing. Every author has made a significant contribution to the research and has concurred revised. Sueb Sueb: review & editing, formal analysis and susbtantially revised.

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