

The Role of Augmented Reality in Transforming Education to Support Sustainable Development Goals: A Literature Review

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Abstract. Access to quality education remains a challenge in developing nations, including Indonesia. Augmented reality (AR) has emerged as a promising tool to address this gap. This review aimed to examine AR applications in education from 2001 to 2024, focusing on their impact on learning outcomes and accessibility. The study analyzed 171 articles selected through a systematic search in databases like scopus and IEEE explore. Key aspects reviewed include AR tools, applications, evaluation methods, and target demographics. Findings highlight AR's effectiveness in STEM education, vocational training, and cultural learning through features like 3D visualizations, interactive simulations, and animations, enhancing engagement and skill acquisition. AR aligns with sustainable development goals 4 (quality education), 9 (industry, innovation, and infrastructure), and 10 (reduced inequality) by improving access to education and reducing inequalities. However, challenges such as inadequate teacher training, limited infrastructure, and the need for localized content hinder broader implementation. The review concludes that AR tools should address pedagogical and contextual needs for optimal impact. Recommendations include expanding teacher training, improving access to technology, and developing culturally relevant content. Future research should explore scalable, long-term AR solutions to enhance global education.

Keywords: Augmented reality; education; transforming education; sustainable development goals; literature review

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Introduction

A ground-breaking invention, augmented reality (AR) combines interactive computer-generated content, such as text, photos, music, video, and animations, with real-world settings. Through the use of mobile devices, headsets, or tablets, AR improves the way information is presented by enabling users to perceive and interact with concepts in more captivating and immersive ways (Bawa, 2022; Munzer, et al., 2019). With the ability to convert conventional teaching techniques into dynamic, interactive learning experiences that foster greater comprehension and long-term retention, this technology has emerged as a crucial element of educational reform. In Indonesia, where issues including insufficient funding, unequal access to high-quality education, and technical inequalities still exist, integrating AR into education is very important. AR provides scalable

tools that may be customized to meet a range of educational demands, offering creative solutions to these problems. For example, through immersive, hands-on learning experiences, AR has been effectively used to improve vocational training, advance STEM education, and support medical education (Hidayat, et al., 2021; Moro, et al., 2020).

According to research, AR promotes cognitive growth and imagery abilities, which are essential for comprehending difficult courses like physics and math. One important aspect of STEM education is spatial reasoning, which AR can improve (Nurbekova & Baigusheva, 2020). Additionally, AR's uses in vocational fields like tourism and agriculture give students the opportunity to learn real-world skills in virtual settings, making it a more affordable option than traditional training techniques. However, despite its revolutionary potential, a number of obstacles stand in the way of AR's widespread adoption in education, particularly in rural regions, such as a lack of proper resources, teacher training, and technological infrastructure. Maximizing the advantages of AR technologies in education requires addressing these obstacles (Wang, et al., 2021). Additionally, there is a need for content localization to incorporate Indonesian cultural elements, which would improve relatability and student engagement (Soegoto, et al., 2022). A key issue remains the effective integration of AR within Indonesia's educational frameworks, ensuring it provides relevant, context-sensitive learning experiences. This study seeks to address these gaps by providing a systematic review of the existing literature on AR's application in education, with a focus on Indonesia. The objectives are to: (i) identify existing AR-based tools used in teaching and learning, (ii) analyze the types of AR components adopted and their alignment with target audiences, (iii) explore evaluation methodologies for assessing the success of AR in education, (iv) examine the factors that contribute to the success or failure of AR implementation, and (v) provide actionable insights for educators, policymakers, and researchers to optimize AR integration in Indonesia's educational system.

In Indonesia's education sector, AR has become a game-changing technology with enormous potential to improve learning outcomes and encourage wider uses (Zeybek & Sayin, 2022). Through immersive, interactive learning experiences that enhance students' comprehension and knowledge retention, AR directly supports sustainable development goal (SDG) 4 on quality education (Mahendru & Neo, 2022; Dhar, et al., 2021). This is particularly significant in addressing educational disparities in Indonesia, where access to quality education remains unequal (Ez-Zaouia, et al., 2022; Finch, et al., 2022). AR supports SDG 9 on Industry, Innovation, and Infrastructure by promoting innovation in the educational sector. AR helps improve infrastructure and provides scalable solutions adaptable to diverse educational settings (Wyss, et al., 2022; Zhu, et al., 2015). AR tools accessible on various devices enable students and educators to use them in different locations, democratizing access to advanced educational technologies (Madi, et al., 2022). By providing equal learning opportunities for all students, irrespective of their location, socioeconomic background, or access to conventional resources, AR helps achieve SDG 10 on reduced inequality (Jdaitawi & Kan'an, 2021; Wei, et al., 2021). Because AR's interactive content accommodates a variety of learning preferences, all students may comprehend difficult subjects more thoroughly (Arakida, 2023; Lee, et al., 2022). The localization of AR content with Indonesian cultural elements enhances its relevance, bridging cultural gaps and making learning more meaningful (Dinh, et al., 2023; Jdaitawi, et al., 2022).

The study's conclusions are intended to help educators and school officials choose and use AR products that improve student learning (Booyoesen, 2023). With an emphasis on its effects in Indonesia, the literature review explores how AR can improve education (Alahmari, 2023; Oueida, et al., 2023). The findings demonstrate that AR-enhanced learning experiences lead to improved academic performance, increased student interest, and better knowledge retention (Sanna, et al., 2015; Tuma, et al., 2022; Ahmad, et al., 2023; Hunaepi, 2023). The results are highlighting the connection between integrating AR and achieving the SDG (Herwin, 2023; Sodervik, et al., 2021). According to the literature review, AR has the ability to improve academic performance through adaptive learning

systems, close the engagement gap, and change traditional classrooms (Dalim, et al., 2017; Vassigh, 2016). Highlighting the significance of ongoing study and funding for AR technologies in order to fully realize their potential in Indonesia's educational system (Shamsudin, 2023). Several SDG are closely aligned with the use of AR in education, and more research into its potential uses can help attain these objective (Chen, 2023; Intarapreecha, 2023).

The study's conclusions demonstrate how important augmented reality is to improving learning outcomes and encouraging wider uses in Indonesia. By enhancing educational quality, encouraging innovation in the field, and providing fair learning opportunities, AR directly supports the attainment of SDG 4, 9, and 10. In order to optimize the advantages of this game-changing technology in Indonesia's educational system, the suggestions made in this paper are meant to assist educators and administrators in choosing and utilizing AR solutions.

Methods

The research plan used in this study includes a methodical approach to finding and evaluating papers that are pertinent to resolving a particular research issue. The PRISMA-P 2015 standards, which offer a defined framework to guarantee consistency, transparency, accountability, and integrity in the review process, were followed in conducting the systematic review. These standards were first created for studies pertaining to health, but they have now become widely accepted in many different fields. Finding data sources, choosing search terms, and creating inclusion criteria were all part of the research methodology. Key highlights from the chosen publications were compiled into tables, and quantitative elements were examined in order to synthesize the results. Data sources the quality of a systematic review starts with the data sources used for identifying the articles to be selected for the review. This requires a thorough search and scrutiny of existing literatures from variety of academic databases and journals. Science direct, scopus, IEEE explore, springer, web of science, google scholar, and wiley online Library are among the scholarly databases and publications taken into consideration for this review. The journals or conference papers that are indexed in these databases are considered to be of high quality and are reliable bibliographic sources.

The literature search approach suggested by Kitchenham, et al., (2009) was used to make sure that pertinent and thorough studies were chosen for this review. This approach seeks to find pertinent studies about AR by using the most appropriate primary search phrases. While a simple search query using the main search string should theoretically yield sufficient results, in practice, it is often necessary to include substrings to ensure the retrieval of all pertinent articles. "Augmented reality," "augmented reality in education," "AR technology in education," "AR impact on learning," "AR tools in teaching," and "AR in vocational education" are the search phrases used to find pertinent content across scholarly databases and journals. According to the elimination procedure described, the number of articles obtained through the database keyword search was decreased by (i) removing papers based on irrelevant titles and duplicates from different sources, which reduced the pool from 72,202 to 19,225; (ii) examining the abstracts of the 19,225 articles, which further reduced the number from 19,225 to 1,911; and (iii) removing papers based on their relevance to the research focus after reading the full text, which reduced the number from 1,911 to 171. Figure 1, which shows the flow of the process for screening the articles for this study on the role of AR in revolutionizing education, shows the elimination technique.

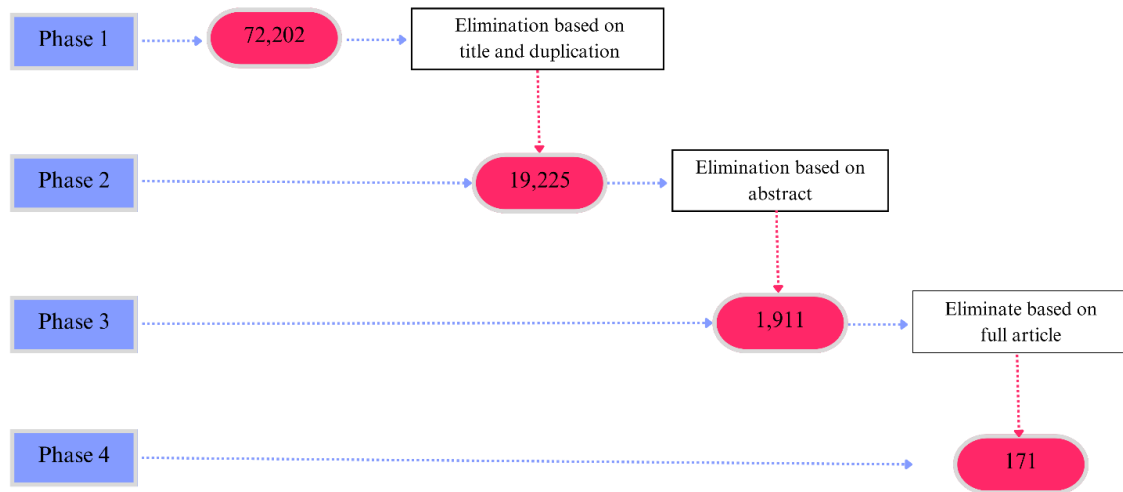


Figure 1. Literature elimination process

Every article that was obtained from the academic databases and libraries that were consulted for this study had an equal probability of being chosen. A specific idea was developed and accepted to determine the criteria for inclusion papers in order to prevent bias in the selection process. Table 1 lists these requirements.

Table 1. Inclusion criteria of article

No.	Inclusion criteria
1.	AR technology, tools, software, applications, impact, and deployment in the educational system are the main topics of the study.
2.	The paper was published in a respectable journal or conference after undergoing peer review.
3.	The research is written in English.
4.	The article is either a research paper or a survey.
5.	The article can be found online.

A total of 72,202 augmented reality-related articles that were published in English and accessible online were found by utilizing the search terms that were supplied. Every publication discovered as of December 2024, the search date, was taken into consideration for inclusion. The selection procedure was conducted without any particular restrictions on the publication date. The following section describes how to filter this collection of papers to fit the study's goals.

After finalizing the selection process, the 171 articles were shortlisted for analysis based on the selection process. After reviewing each article, data was taken out and tabulated. The following details were sought: the kind of augmented reality tool that was utilized, its focal area, the AR components that were integrated into it, how the tool was used, where it was tested, and the age range that the tool was intended for. A "comments" section was also included to the articles to record qualitative information like opinions on the usefulness of AR and user experiences. If the tool was tested, the evaluation process was documented, along with the target group, sample size, results, evaluation restrictions, and generalizability of the results. Insights from the reviewed publications will be provided in the next part, with certain findings condensed into tables to aid in synthesis and analysis.

Results and Discussion

Each of the 171 shortlisted papers underwent a systematic examination that involved information extraction following the meticulous application of the selection procedures. These data were tallied for additional examination. Not every article had the required data items or was empirically based. A summary of the scholarly databases consulted and the quantity of articles retrieved from each source is shown in Table 2.

Table 2. Summary of academic databased

No.	Article sources	URL	Number of articles	Score (%)
1.	Science direct	https://www.sciencedirect.com/	37	21.63
2.	Scopus	https://scholar.google.com/	29	16.96
3.	IEEE explore	http://www.ieeeexplore.ieee.org/	19	11.11
4.	Springer	http://www.springer.com/	31	18.13
5.	Web of science	http://dl.acm.org/	16	9.36
6.	Google scholar	https://apps.webofknowledge.com/	21	12.28
7.	Wiley online library	http://onlinelibrary.wiley.com/	18	10.53
Total			171	100

Table 2 provides a detailed breakdown of the percentage of articles sourced from various academic databases, showcasing that science direct emerges as the most significant contributor with 37 articles, accounting for 21.63% of the total reviewed papers. This is closely followed by springer, which contributes 31 articles (18.13%), and scopus with 29 articles (16.96%). Google scholar also plays a notable role with 21 articles, representing 12.28% of the total. IEEE explore contributes 19 articles (11.11%), while wiley online library and web of science add 18 articles (10.53%) and 16 articles (9.36%), respectively. Together, these statistics highlight the variety of sources analyzed in this investigation on the revolutionary potential of augmented reality to improve education in Indonesia. The conversation now shifts to Figure 2, which provides a chronological view of the advancement and uptake of these technologies by showing the trajectory of augmented reality tools by year of release, from 2001 to 2024.

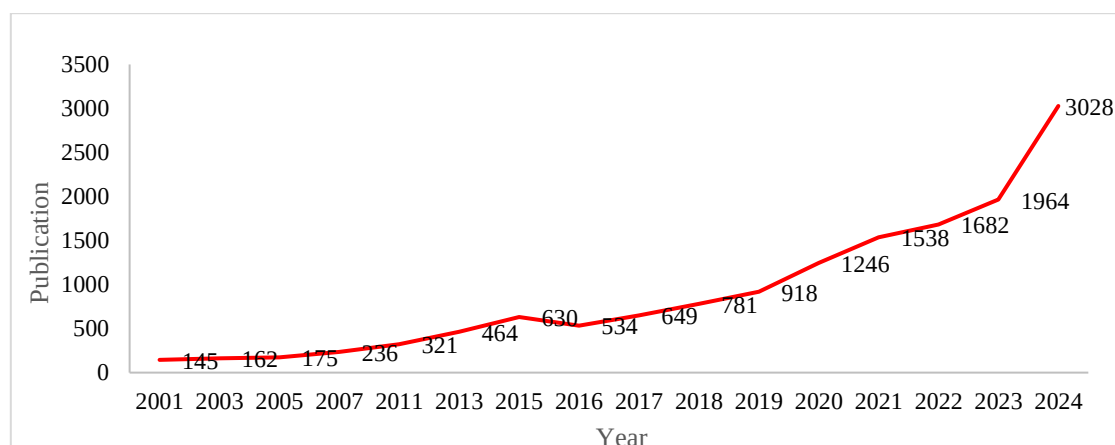


Figure 2. AR tools trend based on year of publication

AR is a powerful educational tool that enhances interactive learning, personalizes instruction, and supports skill development. It enables students to better understand complex and abstract concepts, especially in STEM through immersive experiences like 3D modeling and historical simulations (Arzak & Prahani, 2023; Elmira, et al., 2022; Challenor

& Ma, 2019). AR also supports personalized learning, benefiting diverse learners, including those with learning difficulties (Baharuddin, 2023; Widodo, et al., 2019). In fields like engineering, medicine, and design, AR offers practical simulations that traditional methods often lack (Lazo-Amado & Andrade-Arenas, 2023). Research shows that AR boosts comprehension, engagement, and collaboration, with tools such as AR flashcards and anatomy apps showing measurable improvements (Yu-peng & Yu, 2023). However, challenges remain, high costs, limited access, and a lack of educator training hinder widespread adoption (Batanero, et al., 2022). AR's integration in education also supports SDG, especially SDG 4 and SDG 10, by promoting inclusive and equitable learning. To fully realize AR's potential, it is crucial to address these barriers. As technology advances, AR will play an increasingly important role in shaping the future of education.

AR Tools, Technologies, Components, and Applications

The section that follows provides a thorough overview of the many AR tools, technologies, and their constituent parts in order to examine the wide range of applications and technological aspects of AR tools in education. Table 3 provides a detailed overview of the different AR tools utilized across educational contexts, categorized by their technological components and intended applications. This table highlights the range of AR implementations, from standalone systems to web-based platforms, showcasing how these tools support teaching and learning in diverse educational settings. By examining the components and applications, we gain insights into the innovative ways AR is transforming the educational experience.

Table 3. An overview of AR tools, technology, elements, and educational applications

Publication	AR tool	Stand-alone/ web-based	AR components	Application	
				Teaching	Learning
Alharbi & Osman, (2024)	AR-assisted intraoral scanning (AR-HUD)	Stand-alone	Heads-up display, scanning, digital impression	No	Yes
Boediono, et al., (2023)	Markerless AR for Indonesian traditional house education	Stand-alone	AR plane detection, interactive 3D visualization	Yes	Yes
Boel, et al., (2024)	mixed AR/VR/MR platforms	Stand-alone/web-based	Head-mounted displays, interactive content, teacher training tools	Yes	Yes
Camara, et al., (2024)	AR game-based learning experiences	Stand-alone	Tangible interactions, visualizations	Yes	Yes
Dam, et al., (2024)	audio augmented reality using sonification	Stand-alone	Sonification, audio, visual art	No	Yes
Harnal, et al., (2023)	Various AR applications	Stand-alone/web-based	Digital visual elements, audio, sensory info	Yes	Yes
Ferrari, et al., (2024)	AR-based astronomy apps	Stand-alone	Interactive 3D models, interactive star maps, real-time simulations	No	Yes
Hajirasouli & Banihashemi, (2022)	AR-based learning tools	Stand-alone	Immersive simulation, 3D modeling, visualization	Yes	No
Hu, et al., (2021)	Virtual and augmented reality for structures (VARs)	Stand-alone	Interactive AR models for structural systems	Yes	Yes
Khamitova, et al., (2023)	AR-based linguistic games	Stand-alone	Cultural concept modeling, interactive games	No	Yes
Lai, et al., (2024)	SimEx-plus with EPCAD software	Stand-alone	AR dental training simulator, CAD software	Yes	Yes

Publication	AR tool	Stand-alone/ web-based	AR components	Application	
				Teaching	Learning
Lin & Ironsi, (2024)	Augmented reality	Stand-alone	Simulations, 3D interactive models, AR visualizations	Yes	Yes
Liu, et al., (2022)	AR-based school physical education training	Stand-alone	Visual coaching, immersive AR, IoT, cloud network	Yes	Yes
Meier, et al., (2024)	Projected augmented reality (DIRT)	Stand-alone	Dynamic infrared thermography (DIRT), thermal imaging	No	Yes
Poonja, et al., (2023)	AR and haptics-based STEM learning system	Stand-alone and web-based	AR models, haptics (touch omni device), computer vision (facial analysis, pose estimation)	Yes	Yes
Rahman, et al., (2023)	AR flashcards for learning english words	Stand-alone	Marker-based tracking, vuforia SDK Kit	No	Yes
Rebello, et al., (2024)	AR for chemical engineering	Stand-alone and web-based	Mobile devices (smartphones, tablets), immersive AR resources	Yes	Yes
Vardar-Ulu, et al., (2024)	AR-enhanced molecular case study	Stand-alone	AR objects, 3D molecular visualizations, interactive models	Yes	Yes
Zapata, et al., (2024)	Merge cube (AR)	Web-based	Interactive 3D objects, AR content, escape room, simulations	Yes	Yes
Zhang, et al., (2024)	AR with 6G and capsNet	Web-based	Semantic segmentation, object recognition, real-time interaction	Yes	Yes
Zhou, et al., (2024)	AR-integrated CFD visualisation	Stand-alone	Flow simulations, animations, AR digital twins	No	Yes

Table 4 presents a comprehensive overview of various studies on the use of augmented reality tools in education, detailing their applications, target demographics, and outcomes. Spanning diverse fields, age groups, and geographic regions, the studies illustrate how AR is being creatively applied to enhance educational experiences. From boosting engagement in language and cultural studies to strengthening hands-on skills in dental education, the findings highlight AR's transformative impact across learning contexts. The table also reflects both global trends and localized implementations, combining broad bibliometric insights with case studies from specific countries. This dual perspective provides a well-rounded understanding of AR's expanding role and evolving significance in modern education.

Table 4. Summary of the target age groups for the ar tools

Publication	AR tool	Test location	Target age	Comments
Alharbi & Osman, (2024)	AR heads-up display for intraoral scanning	Clinical study, unspecified location	Adults (10 patients)	AR tool reduced scan time (44s) and image count (836), maintaining accuracy.
Boediono, et al., (2023)	Markerless AR for Indonesian traditional house education	User testing in Jakarta, Indonesia	General public	80% device compatibility with ARCore; 53% of testers found the application easy to use; aims to promote cultural preservation.
Boel, et al., (2024)	Mixed AR/VR/MR platforms	Flanders (Belgium)	K-12 (5–18 years)	Nation-wide implementation framework focusing on teacher training,

Publication	AR tool	Test location	Target age	Comments
Camara, et al., (2024)	AR game-based learning experiences	Lisbon, Portugal	11–13 years old	hardware, and research coordination. The study showed higher learning gains, increased positive affect, and decreased negative affect. Positive attitudes and increased engagement were the results of improved audio. Significant improvement in academic performance in the experimental group. Focus on integrating AR for enhancing learning of architecture and construction curricula. Focused on bibliometric analysis for education
Dam, et al., (2024)	Audio augmented reality using sonification	Art gallery (lab setting)	Adults (26 participants)	
Ferrari, et al., (2024)	AR-based astronomy apps	Secondary school, Spain	12-16 years	
Hajirasouli & Banihashemi, (2022)	AR-based learning tools	Architecture and construction education institutions	Higher education students	
Harnal, et al., (2023)	Various AR applications	global (scopus database study)	Education professionals, researchers	
Hu, et al., (2021)	VARS	Undergraduate classrooms	undergraduate	VARS AR application was tested on non-engineering students to teach structural systems, enhancing their understanding and perception of the subject.
Khamitova, et al., (2023)	AR-based linguistic games	Al-Farabi Kazakh National University	University students (Philology)	Focuses on integrating AR tools for learning linguistic and cultural concepts in Kazakh language education.
Lai, et al., (2024)	SimEx-Plus with EPCAD Software	Dental education facility	Dental students/professionals	SimEx-Plus with EPCAD allowed learners to design restorations and simulate tooth preparation in a virtual environment.
Lin & Ironsi, (2024)	Marketing strategies AR simulation	Business education students	University students	Improved understanding of marketing strategies, higher engagement.
Liu, et al., (2022)	AR-based school physical education training	Schools, unspecified location	School students	Improved student engagement and performance in physical education activities through AR coaching.
Meier, et al., (2024)	Projected augmented reality (DIRT)	Clinical setting, unspecified location	Adults (20 patients)	The study demonstrated high accuracy in projecting DIRT hotspots for perforator localization, with results closely matching Doppler and intraoperative findings.
Poonja, et al., (2023)	AR and Haptics-based STEM learning system	Classroom and online settings	Students (unspecified)	Combined AR and haptics enhanced engagement in STEM learning; computer vision detected engagement levels.

Publication	AR tool	Test location	Target age	Comments
Rahman, et al., (2023)	Learning simple english words using AR	Paired t-tests (effectiveness) and UX Questionnaire	Students (unspecified)	Flashcards paired with AR enhanced learning engagement and effectiveness for basic English vocabulary.
Rebello, et al., (2024)	AR for chemical engineering	Various (review study)	University students	The study emphasized the widespread use of AR in chemical engineering education for complex concepts and skills acquisition.
Vardar-Ulu, et al., (2024)	AR-enhanced molecular case study	Biochemistry & molecular parasitology courses at two institutions	Undergraduate students	AR tools helped bridge the gap between case study and implementation, reducing cognitive load and improving clarity in structure-function discussions.
Zapata, et al., (2024)	Merge cube (AR)	Classroom, high school	65 students (58.5% female, 41.5% male)	This project concentrated on teaching linear equation systems using AR-based learning with Merge Cube. When compared to the conventional teaching approach, the experimental group demonstrated improvements in both mathematics knowledge and motivation.
Zhang, et al., (2024)	AR with 6G and CapsNet	Academic context	All ages (general)	Combines 6G with AR for enhanced interactivity and dynamic learning experiences.
Zhou, et al., (2024)	AR-integrated CFD visualisation	Chemical engineering labs	Undergraduate students	AR-assisted training enhanced laboratory work and introduced digitalisation concepts for industry 4.0.

Table 5 highlights the diversity of focus areas, methodologies, target groups, sample sizes, and outcomes, offering a detailed understanding of how AR tools are assessed for their effectiveness in various educational contexts. The results demonstrate the adaptability of AR tools across disciplines, from dental education and linguistic studies to physical education and engineering. While most studies report positive outcomes, such as improved engagement, skill acquisition, and academic performance, limitations like small sample sizes, regional specificity, and scalability challenges are evident.

Table 5. Summary of evaluation methods for AR tools in education

Publication	Focus area	Evaluation method	Target group	Sample size	Outcome	Limitations	General-izable outcome
Alharbi & Osman, (2024)	Intraoral scanning for dental practice	Comparison of AR-HUD with traditional techniques for scan duration, photo count, and accuracy	10 patients	10	Reduced scan time and image count with no difference in accuracy	Small sample size	Yes
Boediono, et al., (2023)	Indonesian tradition	Feedback survey, ARCore compatibility test	General public	17 testers	80% device compatibility; positive user	Limited sample size,	Yes

Publication	Focus area	Evaluation method	Target group	Sample size	Outcome	Limitations	Generalizable outcome
	al house education				feedback on usability (53% found it easy to use).	regional focus	
Boel, et al., (2024)	Implementation of AR/VR/MR in K-12	Mixed-method surveys, interviews, and teacher feedback	K-12 teachers	200	Improved teacher readiness and interest in AR/VR adoption.	Limited to Flanders region; scalability challenges for wider implementation.	Yes
Camara, et al., (2024)	AR game-based learning	Pre- and post-experience learning gains and affective response analysis	Children (11-13 years)	66	Higher learning gains, increased positive affect, and decreased negative affect	Age and context limitation	Yes
Dam, et al., (2024)	Audio augmented reality in art galleries	Eye gaze metrics, thematic analysis, qualitative feedback	26 participants	26	Positive feeling and increased engagement were the results of improved audio.	Limited to art galleries, small sample	Yes
Ferrari, et al., (2024)	AR in astronomy instruction	Pretest-posttest design, knowledge questionnaire	Secondary students	130	The experimental group's academic performance significantly improved.	Limited to secondary education in Spain; may not be directly applicable to all subjects or age groups.	Yes
Hajirasouli & Banihashemi, (2022)	Architecture and construction Education	Critical analysis, framework development	Architecture & construction students	Not specified	AR holds great promise for improving instructional approaches and student skills in AC education.	Limited implementation of AR tools in current curricula; gap in pedagogical strategies for AR in AC.	Yes
Harnal, et al., (2023)	AR in education	Bibliometric analysis of documents	Researchers, educators	3909 documents	Growth in AR usage, challenges identified	Limited to documents published until 2020	Yes
Hu, et al., (2021)	Structural systems for non-engineering students	Quasi-experiment, questionnaire survey	Undergraduate non-engineering students	103	Posttest quiz results significantly improved, and AR was seen favorably as a teaching method.	Limited to non-engineering students and structural systems	Yes
Khamitova, et al., (2023)	Linguistic and cultural Education	Quasi-experiment, student survey	Kazakh language students	75	Improved understanding of Kazakhstan's cultural concepts, enhanced linguistic knowledge.	Study limited to a specific university, focus on cultural concepts within Kazakh linguistics.	Yes
Lai, et al., (2024)	Dental restoration design and	Measurement of internal gaps in dental crowns	Dental students /Professionals	1 tooth (multiple evaluations)	EPCAD-integrated SimEx-Plus produced restorations	Limited to a single tooth and specific settings tested.	Yes

Publication	Focus area	Evaluation method	Target group	Sample size	Outcome	Limitations	Generalizable outcome
	fabrication				with good internal gaps for clinical application.		
Lin & Ironsi, (2024)	Marketing Strategies AR Simulation	Pre- and post-experience assessment of understanding marketing strategies	University students	112	Improved understanding of marketing strategies and higher student engagement	Limited to marketing strategies course	Yes
Liu, et al., (2022)	School physical education training	Performance data analysis, sports trainer feedback	School students	Unspecified	Enhanced engagement and improved spatial orientation and athletic skills in students.	Costly, complex AR systems; limitations in running simulations on standard devices.	Yes
Meier, et al., (2024)	Medical perforator mapping	Comparison of projected DIRT hotspots with Doppler and intraoperative findings	Adults (20 patients)	133 DIRT hotspots	97.3% accuracy within 1 cm radius for DIRT hotspot verification	Limited to preoperative phase and one specific procedure (ALT flap)	Yes
Poonja, et al., (2023)	AR and Haptics for STEM engagement	User study, computer vision-based analysis	Students (unspecified)	Not specified	Students showed higher engagement with AR and haptics systems compared to traditional methods.	Limited information on demographics and scalability.	Yes
Rahman, et al., (2023)	Learning simple English words using AR	Paired t-tests (effectiveness) and UX Questionnaire	Students (unspecified)	Not specified	Effective learning method with positive user experience scores; fun and interactive experience.	Limited details on demographics and sample size.	Yes
Rebello, et al., (2024)	AR in chemical engineering education	Systematic literature review, bibliometric analysis	University students and teachers	22 articles	AR improved understanding of challenging concepts, increased engagement, and enhanced skill acquisition.	Dependent on existing studies; no primary data collected.	Yes
Vardar-Ulu, et al., (2024)	Molecular case studies (MCS)	Classroom observations, instructor feedback, student engagement	Undergraduate students	Varies	Facilitated instructor preparation, reduced cognitive load, and improved student engagement	Limited to biochemistry and molecular parasitology contexts	Yes
Zapata, et al., (2024)	Solving systems of linear equations	Study that is quasi-experimental and includes a control group	High school students	65	Significant improvement in mathematical knowledge and motivation for the experimental group	Limited to high school students and specific math topic (linear equations)	Yes
Zhang, et al., (2024)	AR and 6G in education	Theoretical discussion, performance optimizations	General academic audience	Not specified	Demonstrates potential for enhancing real-time learning,	No experimental data; focuses on the	Yes

Publication	Focus area	Evaluation method	Target group	Sample size	Outcome	Limitations	General-izable outcome
Zhou, et al., (2024)	CFD visualisation and digital twins	Student performance evaluation, feedback surveys	Undergraduate students	45	engagement, and personalized pathways. Improved flow pattern understanding , reduced handling errors, and enhanced digitalisation knowledge.	technological framework. Limited to chemical engineering contexts	Yes

Trends and Innovations in AR Education Tools

This section summarizes a variety of AR tools used in education, focusing on their components and dual roles in teaching and learning. These tools include stand-alone and web-based platforms, often featuring 3D models, simulations, and sensory elements such as audio, touch, and visuals. Examples include AR-assisted intraoral scanning in dental training (Alharbi & Osman, 2024; Lai, et al., 2024) and AR game-based learning with interactive visualizations (Khamitova, et al., 2023). Some tools, like the AR-BCI interface, integrate brain-computer commands for both instruction and learning (Andrews, 2022), while others focus solely on learner-centered immersive simulations (Hajirasouli & Banihashemi, 2022). While most AR tools are stand-alone, several combine with web-based elements for enhanced flexibility, seen in platforms for chemical engineering and mixed AR/VR/MR environments (Boel, et al., 2024; Rebello, et al., 2024).

These tools span fields such as healthcare, physical education, structural engineering, and STEM, aiming to improve spatial understanding, increase engagement, and simplify complex content (Ferrari, et al., 2024; Liu, et al., 2022; Meier, et al., 2025; Poonja, et al., 2023). Overall, the tools demonstrate AR’s adaptability in education, supporting teachers in content delivery and engaging students through immersive experiences that build skills across diverse areas, including linguistics and technical disciplines (Zapata, et al., 2024). The accompanying graph reflects the evolution of these tools across five categories from 2017 to 2024, highlighting shifting patterns in AR development to meet varied educational needs. The timeline from 2017 to 2024 illustrates the evolution of AR research across five key categories. Display and interaction systems (light orange) show steady but intermittent development, reflecting gradual progress in AR interfaces. Sensory and immersive experiences (green) gain momentum from 2019 and peak in 2021, indicating a growing focus on enhancing AR with multisensory elements like touch, sound, and visuals.

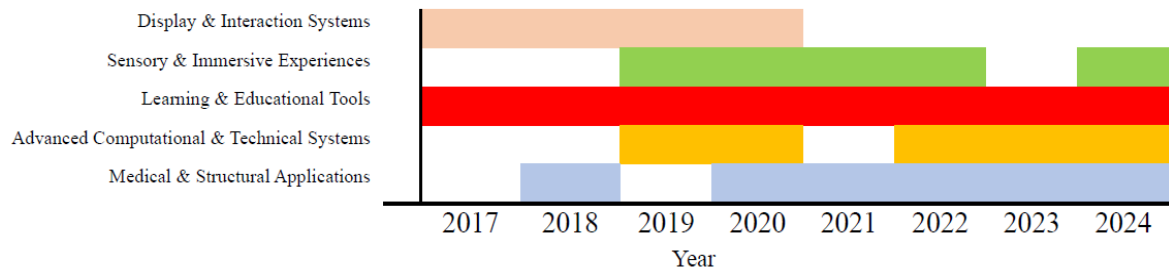


Figure 2. AR tools trend based on year of publication

The most prominent category is learning and educational tools (red), with continuous research from 2019 to 2024, highlighting AR’s increasing role in transforming teaching and learning across disciplines. Advanced computational and technical systems (yellow) rise in

prominence starting in 2019, peaking in 2021 and 2023, showing AR's integration with complex simulations and high-level computing. Meanwhile, medical and structural applications (blue) show concentrated activity in 2020 and 2021, with a slight continuation in 2023, reflecting targeted interest in AR for medical training and structural engineering. Overall, the timeline underscores AR's expanding impact, with a dominant focus on education and immersive experiences, alongside notable advances in technical and medical fields.

Target Age Groups for The AR Tools

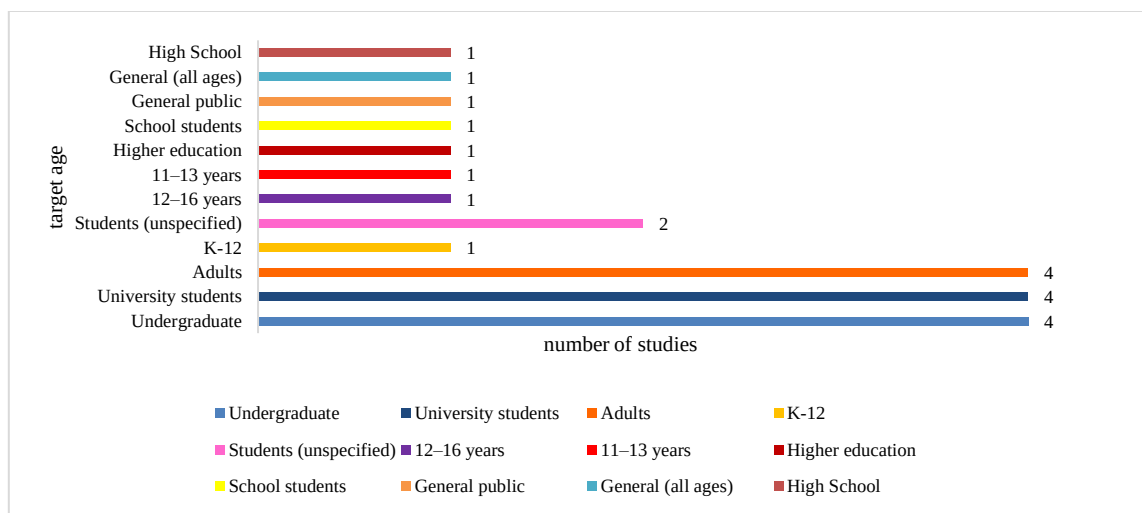


Figure 3. Number of studies by target age group for ar tools in education

AR tools in education are designed for a wide range of age groups and subject areas, from children to adults. For younger learners, tools like AR game-based learning (ages 11–13) and AR-based astronomy apps (ages 12–16) have shown improvements in engagement and academic outcomes. Other tools, such as AR-based physical education systems and linguistic AR games for university students, enhance learning through immersive, interactive methods (Khamitova et al., 2023). In higher education, AR is applied to specialized subjects like dentistry, architecture, and engineering. Tools such as VARS for structural systems and AR platforms for chemical engineering help students grasp complex technical concepts (Hu et al., 2021; Vardar-Ulu et al., 2024). For adult learners and professionals, AR technologies, including intraoral scanning with heads-up displays and DIRT for clinical training, support skill development in healthcare settings. Additionally, AR tools for the general public promote cultural education and heritage preservation through engaging visual experiences. These diverse applications demonstrate AR's broad educational potential across different age groups and learning contexts, including physical education, STEM, healthcare, and cultural studies.

Evaluation Methods for AR Tools in Education

Researchers employ diverse assessment methods to evaluate the effectiveness of AR technologies in education, each offering distinct insights (Figure 4). Quasi-experimental designs, like those used by Lin & Ironsi (2024), assess learning outcomes by comparing groups with and without AR interventions, providing quantitative evidence of AR's positive impact, supported by studies such as Santiago (2023) and Dhar et al. (2021). Bibliometric analyses, such as those by Harnal et al. (2023), identify research trends and emerging AR applications, offering a macro-level view of the field. These analyses, along with studies by Harnal (2023) and Velarde-Camaqui (2024), help guide future research directions. Broader reviews by Boediono et al. (2023), Hajirasouli & Banihashemi (2022), Hu et al. (2021), Lai

et al. (2024), Rebello et al. (2024), and Meier et al. (2025) further contribute to understanding AR's evolving role in diverse educational settings.

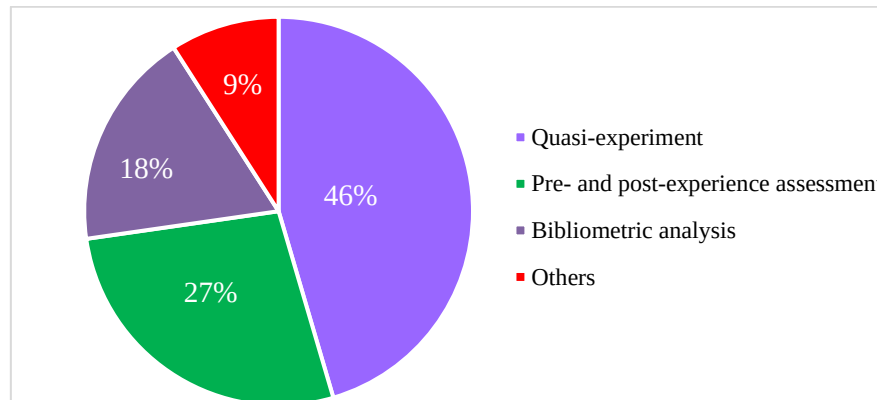


Figure 4. Evaluation method for AR tools in education

User feedback surveys offer valuable qualitative insights into the usability and effectiveness of AR tools. For example, Boediono et al. (2023) used surveys to identify both strengths and improvement areas, while Rahman et al. (2023) applied paired t-tests to evaluate an AR-enhanced flashcard system, finding significant gains in vocabulary retention. Combining qualitative and quantitative data provides a more complete understanding of AR's educational benefits and limitations. Sari et al. (2025) showed that the use of AR technology in chemistry learning is an effective innovative solution in improving students' understanding and higher-order thinking skills (HOTS).

However, challenges persist. Small sample sizes, like in Dam et al. (2024) limit generalizability, and regional constraints noted by Boel et al. (2024) emphasize the need for culturally inclusive research. To expand AR's impact in education, future studies should prioritize large-scale, multi-site research and adapt tools to local contexts. Cost-effective, user-friendly designs are also essential to ensure global accessibility. By applying comprehensive evaluation methods and addressing these limitations, researchers can refine AR tools to maximize their educational effectiveness and reach a broader, more diverse audience.

AR Tools in Teaching and Learning

The integration of AR in education has become a transformative strategy, offering immersive and interactive experiences across disciplines. AR tools range from stand-alone apps to web-based platforms, enhancing teaching methods and student engagement. Tools like the AR-BCI Interface, which combines brain-computer interaction with neural commands (Scargill et al., 2021), and Mixed AR/VR/MR platforms with head-mounted displays (Hasbi & Yunus, 2021), support teacher training and instructional innovation (Cruz et al., 2021). AR also boosts student motivation and learning outcomes across age groups. Game-based AR tools promote active learning among younger students (Judijanto, 2024; Setiyaningsih et al., 2021), while AR flashcards improve English vocabulary acquisition through interactive, marker-based tracking (Arief et al., 2023; Kiourexidou, 2024). In secondary education, AR-based astronomy apps simplify abstract concepts through real-time 3D simulations (Luckyardi et al., 2022; Saputri & Susilowati, 2022). In technical fields, tools like SimEx-Plus and AR-based learning platforms help students develop practical skills in architecture, construction, and dentistry (Giri, 2024; Nasirudin, 2024).

Engineering students benefit from AR-integrated CFD visualizations and AR applications for chemical engineering that enhance conceptual understanding and lab performance (Yao et al., 2023; Zhang & Robb, 2021; Zhang et al., 2024). AR also supports

cultural education through tools like Markerless AR for Traditional House Education, which uses interactive 3D models to foster cultural awareness and historical understanding (McNally & Koviland, 2024; Liang et al., 2021). Overall, AR improves comprehension, engagement, and skill acquisition by making complex material more accessible and interactive (Torresani et al., 2021). As AR technology advances, its educational benefits for both teachers and students are expected to grow further.

AR Tool Components, Technology, and Uses in Education

AR tools have transformed traditional education by offering immersive, interactive learning across various subjects. Core AR components include hardware like smart glasses and head-mounted displays that overlay digital content onto the real world (Singh, 2019), along with 3D models, simulations, and sensory feedback such as sound and haptics to enhance engagement and understanding (Kocak et al., 2019; Jdaitawi & Kan'an, 2021; Taha, 2023). Technological advancements, such as computer vision, motion tracking, and real-time rendering, enable precise integration of digital elements with physical environments (Yegorina et al., 2021; Olexa et al., 2022; Mokmin, 2022; Shamsudin, 2023; Alahmari, 2023). These technologies are accessible via mobile and specialized AR platforms, making implementation possible in classrooms, labs, and clinical settings (Asham, 2023).

AR applications span multiple disciplines, including healthcare, engineering, and language learning (Majeed & Ali, 2020). In medical education, AR supports tools like intraoral scanning for safe virtual practice. In STEM, AR combines 3D models and haptic feedback to help students grasp scientific concepts, while astronomy apps offer real-time simulations. In design and construction, AR allows learners to interact with complex structures (Sidhu & Iqbal, 2021; Vivianti & Ratnawati, 2021). Language learning also benefits from AR games and cultural modeling that make linguistic instruction engaging. In technical fields like chemical engineering, AR supports visualization of complex systems and real-time interaction, enhancing comprehension and skill development. As the technology evolves, AR is expected to offer even more dynamic, personalized learning experiences across educational domains (Sazly et al., 2021; Talib et al., 2022).

Targeted AR Solutions

AR tools support both teaching and learning, with 17 tools identified as serving dual functions, demonstrating AR's adaptability in addressing diverse educational needs (Rahman, 2024; Limbong et al., 2023). Language AR games enhance student acquisition (Khamitova et al., 2023), while marketing simulations improve teaching strategies (Limbong et al., 2023). In physical education, AR helps teachers demonstrate techniques and gives students real-time feedback (Liu et al., 2022), promoting participatory learning (Apriza, 2024).

AR is also versatile across age groups and settings, from K-12 to professional training (Giancaspro, 2023; Tuli et al., 2022). Middle schoolers use AR for virtual dissections (Booyoesen, 2023), and dental students for clinical practice (Lai et al., 2024). Beyond classrooms, AR enhances experiences in art galleries (Dam et al., 2024) and clinical environments (Meier et al., 2025). Evidence shows AR improves engagement, understanding, and performance (Darmawan, 2024; Neri, 2024; Tuma, 2023). AR games boost science comprehension and emotional involvement (Camara et al., 2024), while tools like SimEx-Plus enhance dental students' confidence and skill. These benefits stem from AR's immersive, interactive nature and real-time feedback.

Success Factors

AR has significant potential to boost student motivation and engagement, making it a key success factor in educational settings. Through immersive and interactive experiences, such as 3D models, animations, and simulations, AR allows students to grasp complex concepts more concretely than traditional methods. This is especially effective in STEM education, where students can manipulate virtual objects, run simulations, and receive real-time feedback, leading to better problem-solving skills and deeper engagement. Moreover, AR supports personalized learning by catering to diverse learning styles and paces. Visual learners benefit from 3D content, while auditory learners gain from sound-based simulations. Real-time feedback helps students quickly identify and correct mistakes, reinforcing understanding and improving retention.

AR also bridges theory and practice, particularly in fields like healthcare, engineering, and architecture. It offers students the chance to apply knowledge in realistic yet safe environments—for instance, rehearsing medical procedures virtually before working with real patients. This practical experience is crucial for professional readiness. The accessibility of AR across devices: smartphones, tablets, and headsets further enhances its scalability, allowing integration across K-12, higher education, and informal learning settings. Its capacity to increase engagement, personalize learning, connect theory to practice, and offer flexible implementation underscores AR's transformative role in modern education (Putra, 2024).

Conclusion

This analysis emphasizes how important augmented reality is to improving education, especially in the areas of STEM education, career training, and cultural education. The results of an analysis of 171 studies conducted between 2001 and 2024 support the idea that AR can enhance accessibility, learning outcomes, and engagement. Through the reduction of educational inequities and the promotion of innovation, AR helps fulfill SDG 4, 9, and 10. Widespread adoption is nevertheless hampered by issues like inadequate teacher preparation, limited infrastructure, and the requirement for locally relevant information. To maximize AR's impact, future efforts should focus on improving technological access, enhancing pedagogical integration, and developing culturally relevant materials. Further research is needed to establish scalable and sustainable AR solutions for global education.

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