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Augmented Reality in Learning Geometry: A Review of its Advantages and Challenges

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Abstract
The evolution of technology has become an essential part of life, especially in education. Technology in education continues to evolve with innovative learning approaches that aim to meet the needs of the 21st-century learning environment. The use of Augmented Reality (AR) technology is among the key transformations in education. The integration of AR in mathematics education enriches learning experiences and addresses multiple educational challenges by making abstract concepts more accessible and engaging to students. AR is a technology that blends digital elements with the real world, enabling students to interact visually and manipulate geometrical objects. This technology fosters an interactive learning environment that enables teachers to effectively guide their students in understanding geometric concepts. Thus, this research aims to systematically review the latest literature on the use of AR technology in mathematics education, specifically in learning geometry, and to explore its advantages and challenges. The methodology of this study employed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach, using two databases: Scopus and Web of Science. This study analyzed publications from 2022 to March 2025, with a total of 31 selected articles. The findings indicate an increasing trend in the use of AR technology in learning geometry, with secondary school students being the most frequently studied population by previous researchers. The review identified several advantages of AR technology, including improvements in achievement and learning outcomes, enhanced visualization and spatial skills, increased motivation and interest, support for student-centered learning, development of problem-solving abilities, and improved memory retention. However, the review also identified several challenges in applying AR, including technical and resource limitations, pedagogical barriers, and learner-related challenges.
Keywords: Augmented Reality, Advantages, Challenges, Mathematics, Geometry

Introduction

The advancement of technology continues to evolve rapidly and has become an integral part of modern life. Technological devices, such as computers, tablets, and smartphones, are now widely used as supportive tools and as essential instruments for enhancing efficiency, productivity, and the overall quality of daily life (Korkmaz and Morali, 2022). Furthermore, technology has created new opportunities for innovation and development across various sectors, including education. Although the integration of technology in education is not a recent development, its significance is growing as educators strive to equip students with the digital competencies necessary to succeed in a fast-paced and interconnected world. The trend of incorporating technology into education is expected to continue expanding, paving the way for more innovative, context-rich, and engaging learning experiences that align with the demands of 21st-century education. Technological integration substantially transformed pedagogical practices and plays a pivotal role in enhancing teaching and learning by making it more engaging, interactive, and effective. It enables educators to design more impactful instructional strategies, improve content delivery, enrich students' learning experiences, facilitate students' access to diverse information, and tailor the learning process to their individual needs.

The ongoing integration of technology, such as Augmented Reality (AR), has initiated a transformative shift in education. Aligning with the vision of the Fourth Industrial Revolution (IR 4.0), AR-based learning applications have demonstrated significant potential in attracting students and supporting effective learning (Hanid et al., 2022a). With AR's unique ability to blend digital and real worlds, this technology creates opportunities to enhance the quality of teaching and learning. Teachers can leverage AR to cater to students' varied learning preferences and needs, creating more engaging and immersive learning experiences (Rohendi et al., 2025). Moreover, AR supports constructivist learning principles by enabling students to actively construct knowledge through the exploration and manipulation of virtual objects, particularly in subjects that require visualization and comprehension of abstract concepts.

Geometry is one of the foundational branches of mathematics that focuses on the properties and relationships of points, lines, surfaces, and solids. However, it remains a significant challenge for students, especially at the school level. This is mainly due to the abstract nature of geometric concepts, which require strong visualization skills, particularly when working with two-dimensional and three-dimensional shapes. Previous studies have demonstrated that students often develop misconceptions in geometry as they struggle to form accurate mental representations, which are attributed mainly to the use of traditional teaching methods and textbook-based instruction that emphasize rote memorization rather than conceptual understanding (Ismail et al., 2020). Consequently, verbal explanations alone are often insufficient for students, underscoring the need for visual support to facilitate more effective learning. Therefore, incorporating interactive tools such as AR into the curriculum can significantly enhance learning by making abstract concepts more tangible, explicit, and interactive (Rohendi et al., 2025).

Literature Review

Augmented Reality in Education

AR refers to a technology that integrates real and virtual objects in a single environment, enabling real-time interaction and the presentation of scenes in three dimensions (Azuma, 1997), which permits users to view virtual objects displayed superimposed on the real world. The potential of AR in education is vast, particularly in strengthening knowledge and understanding. It can support students across various educational levels, from preschool to college (Koparan et al., 2023). AR provides users with interactive and immersive environments by integrating digital information, such as images, text, videos, and three-dimensional objects, into the real world (Tan et al., 2022). The visualization elements from AR help to enhance students' comprehension of fundamental concepts and topics that are typically difficult to grasp. By offering an interactive simulation experience, AR enables students to interact directly with virtual objects and visualize abstract concepts more effectively, thereby reinforcing their understanding of key learning concepts. It also facilitates the conceptualization of phenomena that are challenging to observe or invisible (Koparan et al., 2023).

Another advantage of AR lies in its potential to address teaching challenges related to students' poor concentration, lack of self-confidence, and inadequate prior knowledge (Liono et al., 2021). Pedagogically, AR can be effectively integrated into teaching and learning to promote independent learning within and beyond the classroom environment (Yaniawati et al., 2023). Through the incorporation of various digital objects in an interactive environment, AR creates opportunities for students to engage with diverse learning modalities (Hui et al., 2024). As highlighted by Beisenbayeva et al. (2024), AR facilitates personalized learning experiences by adapting content to suit individual students' needs and preferences. It also accommodates various learning styles, paces, and abilities through the provision of customized instruction and feedback, enhancing the learning process. Additionally, the use of AR offers direct interaction and experiences that blend virtual elements with the physical world, increasing students' engagement and stimulating their imaginations through an immersive and interactive learning environment (Heydemans and Elmunsyah, 2024). Hence, AR enhances student motivation, fosters collaboration and meaningful interaction between teachers and students in the classroom (Korkmaz and Morali, 2022).

Integration of Augmented Reality in Learning Geometry

Geometry is a field that requires active exploration to foster conceptual understanding, reinforce the memorization of formulas, and comprehend interrelated concepts. Nevertheless, due to the abstract nature of geometrical concepts, students often face significant challenges in comprehending fundamental principles, reasoning, and problem-solving in geometry (Nadzeri et al., 2024). AR technology has emerged as a viable alternative to traditional tools in facilitating geometry learning, particularly at the school level (Hwang, Lin, et al., 2023). The advancements of AR technology have revolutionized the teaching and learning of geometry by introducing interactive and immersive instructional pathways (Tarng et al., 2024). By bridging traditional pedagogy with technology, the integration of AR enriches learning experiences and reshapes the pedagogical landscape of geometry instruction (Tursynkulova and Madiyarov, 2023).

The use of virtual manipulatives via AR fosters deeper conceptual understanding compared to the use of limited physical materials (Singh et al., 2024). AR supports real-time interaction with three-dimensional objects, offering students opportunities to explore geometric figures from multiple perspectives, thereby deepening their understanding of spatial relationships and properties (Rohendi et al., 2025), which is crucial for mastering geometry. Furthermore, AR assists students in connecting textbook-based examples to their real-world environments through real-time demonstrations (Wang et al., 2024). By offering simulation and exploration activities, hands-on experience with AR can promote the mastery of both conceptual and procedural knowledge while simultaneously enhancing spatial understanding and reducing cognitive load that has traditionally been a barrier in geometry education (Nadzri et al., 2024; Tarng et al., 2024). These advantages demonstrate how AR technology in geometry learning enhances conceptual understanding, strengthens students' long-term memory (Nadzri et al., 2023), and fosters psychological states such as motivation (Uriarte-Portillo et al., 2023). Additionally, it improves students' mathematical problem-solving abilities (Nindiasari et al., 2024), enhances spatial reasoning (Rahman and Halim, 2024), and develops Higher Order Thinking Skills (HOTS) (Pujiastuti and Haryadi, 2023b).

Significance and Objectives of the Study

This study highlights the integration of AR technology in geometry learning, aligning with current learning needs that emphasize the use of technology to convey abstract concepts in a more concrete, accessible, and comprehensible manner. Although numerous studies have reviewed the effectiveness and influence of AR in Mathematics education (Bulut and Ferri, 2023; Erşen and Alp, 2024; İslim et al., 2024; Ivan and Maat, 2024; Jabar et al., 2022; Korkmaz and Morali, 2022; Pahmi et al., 2023), there remains a scarcity of research specifically reviewing the advantages and challenges associated with the use of AR in the context of teaching and learning geometry.

The main contribution of this study lies in providing a structured synthesis of the key advantages and challenges associated with implementing AR technology in learning geometry within mathematics education. Overall, this review strengthens the understanding of the current landscape of AR use in geometry teaching and learning, and further research can more effectively harness the potential of this technology. Specifically, this Systematic Literature Review (SLR) aimed to explore the following research questions:

1. What are the distributions of the AR technology in learning geometry according to the year of publication and sample group?
2. What advantages does AR technology offer for learning geometry?
3. What challenges are encountered when using AR technology in learning geometry?

Methods

This research used the SLR approach to identify, evaluate, and synthesize previous studies related to the use of AR technology in mathematics education, specifically in learning geometry. The study procedure was structured according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, as outlined by Moher et al. (2009). PRISMA offers three advantages: 1) it defines clear research questions that permit systematic research, 2) it identifies the inclusion and exclusion criteria, and 3) it attempts to examine an extensive database of scientific literature in a defined time (Hanid et al., 2020). Moreover, the PRISMA approach was chosen because it provides a transparent, comprehensive, and evidence-based reporting structure for conducting systematic reviews, allowing readers to evaluate the procedures and credibility of the study (Sarkis-Onofre et al., 2021). The process implemented in this study consisted of four main phases: identification, screening, eligibility assessment, and inclusion, as summarized in Figure 1.

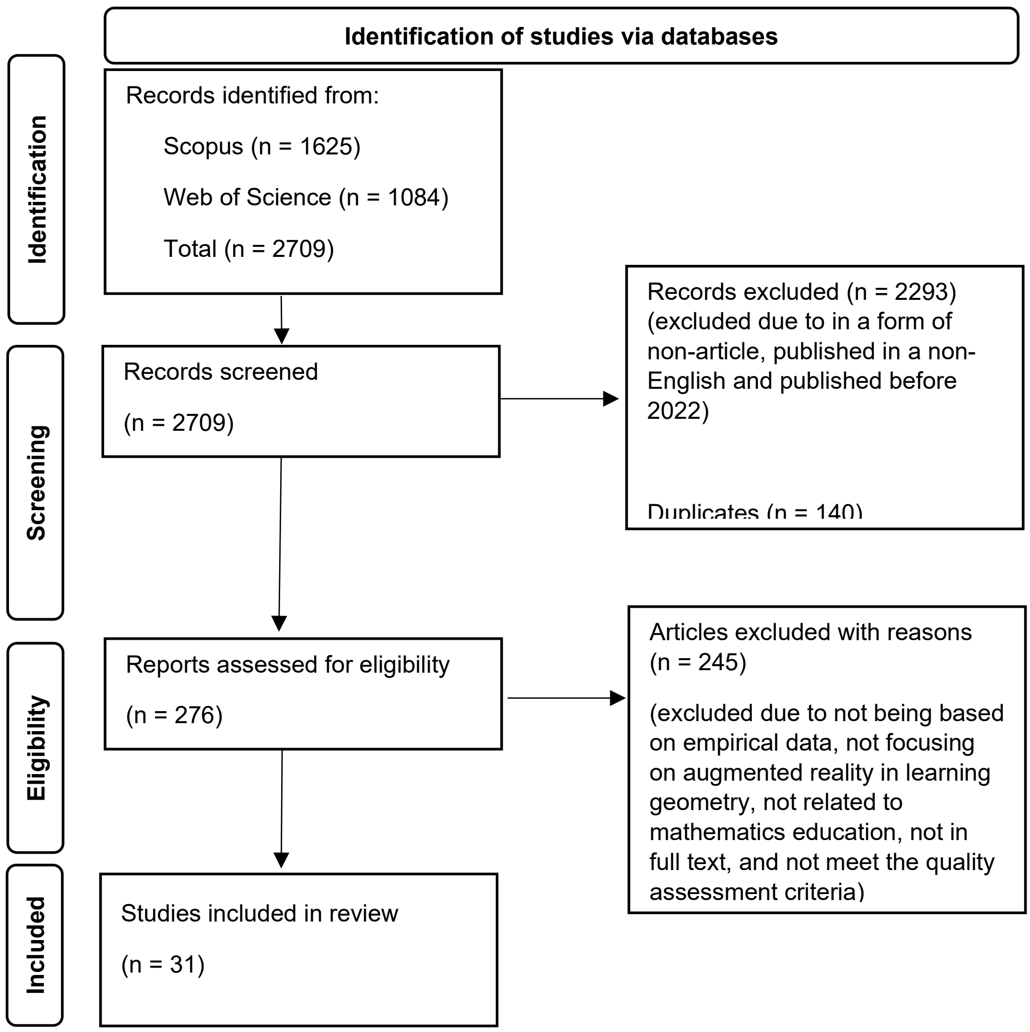

Figure 1. Flow diagram of the study

In the identification phase, essential steps of the systematic review process were employed to collect a significant body of relevant literature. Searches were conducted in two major databases: Scopus and Web of Science. In particular, only these two databases were selected for the literature search as they provide analytical tools that allow researchers to assess the impact and influence of published studies using metrics such as citation counts and the h-index. Moreover, if the chosen database is recognized for its stringent quality control, researchers are more likely to regard it as a trustworthy source of credible and scholarly publications (Hui et al., 2024). Keywords such as “augmented reality” and “geometry” were used to ensure relevance to the study objectives (see Table 1). Therefore, this phase was critical for laying the foundation of the review by gathering a wide array of potentially relevant studies that explore the integration of AR technologies in learning geometry. This initial stage of the systematic review yielded 2,709 publications related to the study topic from the two databases.

Table 1
Search terms used in the systematic review process

Databased	Boolean operator used
Scopus	TITLE-ABS-KEY (“augmented reality” AND “geometry”)
Web of Science	ALL = (augmented reality) AND (geometry)

In the subsequent screening phase, the potential research articles were further scrutinized to examine their suitability for inclusion in the review. Initially, 2293 publications were excluded based on specific inclusion and exclusion criteria (see Table 2). The first criterion was the type of literature, which was limited to journal articles and excluded reviews, meta-syntheses, meta-analyses, books, book series, chapters, and conference proceedings. The review was also limited to English-language publications from 2022 to March 2025. Moreover, duplicate papers are also removed at this stage. After eliminating 140 duplicates, a total of 276 articles proceeded to the next stage. Consequently, this rigorous filtering ensured that only suitable and relevant publications were retained for further evaluation.

Table 2
Inclusion and exclusion criteria used

Criteria	Inclusion	Exclusion
Literature type	Journal (Article)	Conference, Book, Review
Language	English	Non-English
Timeline	2022 – March 2025	< 2022

In the following step, known as the eligibility phase, 276 articles that had passed the initial screening were prepared for a detailed assessment. During this stage, the titles and key content of all articles were carefully examined to ensure they met the inclusion criteria and aligned with the research questions. Consequently, 245 articles were excluded because they did not qualify due to not having full text, being out of the field, the title not being significantly related, the abstract not being related to the study’s objective, or no empirical data being revealed. Subsequently, the quality of the articles was appraised by the authors using the Mixed Method Appraisal Tools (MMAT) developed by Hong et al. (2018), based on the tools’ assessment criteria, which were specifically designed to evaluate the quality of empirical studies. As a result, a total of 31 articles remain for further review.

The final inclusion phase resulted in the selection of 31 articles that met all specified criteria. Eligible studies were required to: (1) present empirical findings, (2) explicitly involve AR in the context of learning geometry, and (3) be related to mathematics education. The reviewed studies provide critical insights into both the potential advantages and the challenges associated with integrating AR technology into learning geometry within mathematics education. Moreover, the application of this structured four-phase process, in alignment with PRISMA guidelines, ensured a transparent, reproducible, and academically rigorous foundation for exploring the integration of AR in learning geometry. The reviewed studies are summarized in Table 3 and will be elaborated further in the results and discussion sections.

Table 3
Summary of the reviewed study

No	Author(s) and Year	Samples	Purpose of Study
1	Beisenbayeva et al. (2024)	82 tenth-grade students (high school)	To evaluate the influence of an AR mobile application on improving secondary students' visualization and comprehension of geometric concepts.
2	Faizah et al. (2024)	10 prospective elementary school teachers	To investigate the level of geometric thinking of prospective teacher students after using the AR Digital Module Instruction (ADMI).
3	Gargrish et al. (2022)	54 twelfth-grade students (high school)	To explore the use of AR in mathematics for geometry education, to aid visualization of multidimensional objects and long-term retention of concepts by the learners.
4	Hakim et al. (2024)	68 public junior high school students (secondary school)	To develop MoAR-Integrated Printed Learning Modules to improve Mathematical problem-solving abilities in geometry learning.
5	Hanid et al. (2022a)	124 Form One students (secondary school)	To investigate the effect of AR application on computational thinking, visualization skills, and geometry topic achievement.
6	Hanid et al. (2022b)	10 Form One students (secondary school)	To analyze the computational thinking elements in solving the geometry topic after the intervention of the AR application.
7	Hwang, Lin, et al. (2023)	52 fifth-grade students (elementary school)	To investigate the effectiveness of smart mechanisms on geometry learning supported by a mobile application with the integration of AR (Smart-UG).
8	Hwang, Nurtantyana, et al. (2023)	50 fourth-grade students (elementary school)	To develop an Authentic GeometryGo (AGG) app to help students' application of geometry in authentic contexts through authentic measurements and peer assessments.
9	Koparan et al. (2023)	98 fifth-grade students (secondary school)	To design, develop, and reveal the effect of an AR material to improve spatial ability in secondary school students using mobile devices.
10	Mandala et al. (2025)	18 eighth-grade students (secondary school)	To develop mobile AR-based geometry learning games to facilitate spatial reasoning.
11	Na and Sung (2025)	38 fourth-grade students (elementary school)	To design an AR-based embodied learning game for geometry learning in classroom settings and explore its impact on students' varied engagement during their embodied learning.
12	Nadzeri et al. (2023)	52 mathematics teachers	To gain insight into teachers' perspectives on the development of AR applications in the geometry topic for elementary school.
13	Nadzeri et al. (2024)	61 second-grade students (elementary school)	To investigate the effects of AR technology in primary school education on students' spatial visualization abilities in geometry.

14	Nadzri et al. (2023)	59 Year Four students (elementary school)	To determine the effects of using a module with AR compared to a module without AR integration in learning geometry among pupils in primary school.
15	Nadzri et al. (2024)	59 Year Four students (elementary school)	To identify the effectiveness of using AR modules on students' conceptual and procedural knowledge in geometry.
16	Nindiasari et al. (2024)	30 high school students (high school)	To develop AR learning media with STEAM learning for 3D material in geometry to improve mathematical problem-solving skills.
17	Pujiastuti and Haryadi (2023a)	60 eighth-grade students (secondary school)	To determine the effectiveness of Guided Inquiry Learning - Augmented Reality (GILAR) on mathematical literacy ability.
18	Pujiastuti and Haryadi (2023b)	82 eighth-grade students (secondary school)	To determine the effectiveness of using hybrid learning with AR to improve the high-level thinking skills in geometry.
19	Richardo et al. (2023)	18 junior high school students (secondary school)	To develop an Android-based mathematics learning media using AR technology in an ethnomathematical context.
20	Rohendi et al. (2025)	56 eighth-grade students (secondary school)	To investigate the level of students' interactivity and responses when using AR geometry as a learning medium.
21	Singh et al. (2024)	127 first-year engineering students	To investigate the impact of AR technology on the spatial skills and conceptual knowledge of students.
22	Sudirman et al. (2022)	28 eighth-grade students (secondary school)	To investigate the potential of learning that integrates AR technology into the 6E I3DGM module in fostering students' 3D geometric thinking process.
23	Tarng et al. (2024)	66 fifth-grade students (elementary school)	To develop and explore the impact of using the AR Mobile Learning System (ARMLS) to teach elementary geometry on students' learning achievement, learning motivation, cognitive load, and technology acceptance.
24	Tursynkulova and Madiyarov (2023)	42 ninth-grade students (secondary school)	To discern and articulate the unique contributions of AR as a pedagogical tool in 2D plane geometry.
25	Uriarte-Portillo et al. (2023)	106 ninth-grade students (secondary school)	To assess the learning effectiveness and the impact on motivation of using an Intelligent Tutoring System with an AR interface for practicing the basic principles of geometry.
26	Walkington et al. (2024)	28 high school students (high school)	To investigate new forms of functional body actions and gestures when exploring geometry conjectures in an AR-based Dynamic Geometry Software (DGS) related to perspective, scale, and three dimensions.
27	Walkington et al. (2025)	120 high school students (high school)	To determine which approach is more effective for learning geometry using a tablet or AR headsets, and whether this effectiveness varies based on the type of shape, specifically 2D or 3D.
28	Wang et al. (2024)	86 sixth-grade students (elementary school)	To investigate the impact of an AR-integrated Mathematics Curriculum (ARiMC) on students' spatial skills at elementary school.

29	Wu et al. (2024)	83 fourth-grade students (elementary school)	To explore the effectiveness of AR mathematical picture books in improving students' geometric thinking and explore their effects on students' cognitive load and flow experience.
30	Yaniawati et al. (2023)	26 eighth-grade students (secondary school)	To explore the potential of mobile AR as a didactic and pedagogical source, as seen from the implementation design, student responses, and geometry understanding.
31	Yanuarto et al. (2024)	90 seventh-grade students (secondary school)	To examine the comparative effectiveness of traditional and digital approaches in mathematics education, assess students' motivation, and evaluate the impact of technology integration on learning outcomes in the classroom.

Results

Distributions of AR Technology According to Year of Publication and Sample Group

Figure 2 presents the distribution of selected articles published in this systematic review between 2022 and March 2025.

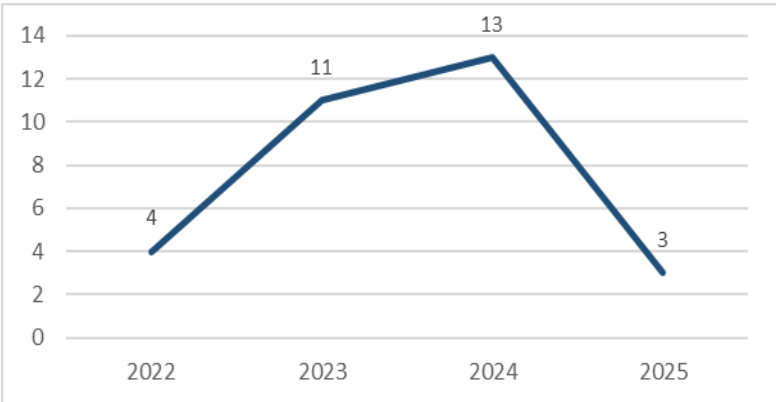

Figure 2. Number of studies based on year

Based on Figure 2, the publication trend demonstrates consistent growth from 2022 through March 2025. There was a significant increase in article publications, from four in 2022 to 11 in 2023, a rise of seven articles. The upward trend continued in 2024, reaching 13 articles, marking the highest annual count so far. By March 2025, three additional studies had already been documented, suggesting that the growth in publications may persist throughout the year. However, generalization for 2025 cannot be conclusively determined, as the year had not yet concluded when this study was conducted.

Figure 3 illustrates the distribution of studies across different sample groups.

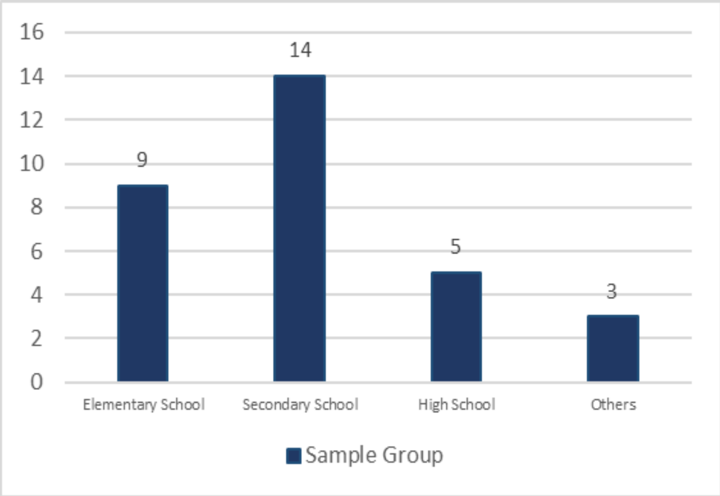

Figure 3. Number of studies based on a sample group

Based on Figure 3, secondary school students were the most frequently studied demographic, appearing in 14 articles, followed by elementary school students with nine articles and high school students with five articles. Studies involving teachers and university students, categorized as “others,” accounted for only three articles. These findings indicate a predominant research focus on secondary school populations in AR-based geometry education, possibly due to the perceived relevance of AR usage among younger learners.

Advantages of AR Technology in Learning Geometry

The reviewed literatures highlight six main advantages of AR for geometry learning. The most prominent advantages identified were improved achievement and learning outcomes, with 13 articles, followed by enhanced visualization and spatial skills, with 11 articles. Seven articles identified AR’s ability to increase student motivation and interest, while six articles noted its effectiveness in promoting student-centered learning and the development of problem-solving skills. Additionally, three articles examined the effect of AR on memory retention. These findings demonstrate that AR offers multidimensional value for geometry education, with the strongest evidence supporting its cognitive benefits. Table 4 summarizes the advantages of AR technology in learning geometry in the reviewed studies.

Table 4
Summary of the advantages of AR technology in learning geometry

Advantages	Authors	Frequency
Achievement and Learning Outcomes	Beisenbayeva et al. (2024), Hanid et al. (2022a), Hwang, Lin, et al. (2023), Hwang, Nurtantyana, et al. (2023), Mandala et al. (2025), Na and Sung (2025), Nadzeri et al. (2023), Nadzri et al. (2023), Nadzri et al. (2024), Pujiastuti and Haryadi (2023a), Ricardo et al. (2023), Tarng et al. (2024), Tursynkulova and Madiyarov (2023)	13
Visualization and Spatial Skills	Faizah et al. (2024), Hanid et al. (2022a), Koparan et al. (2023), Mandala et al. (2025), Nadzeri et al. (2024), Nadzri et al. (2023), Singh et al. (2024), Sudirman et al. (2022), Walkington et al. (2024),	11

	Wang et al. (2024), Yaniawati et al. (2023)	
Motivation and Interest	Hakim et al. (2024), Nindiasari et al. (2024), Pujiastuti and Haryadi (2023b), Rohendi et al. (2025), Uriarte-Portillo et al. (2023), Wu et al. (2024), Yanuarto et al. (2024)	7
Student-Centered Learning	Hwang, Nurtantyana, et al. (2023), Koparan et al. (2023), Nadzeri et al. (2024), Nadzri et al. (2024), Walkington et al. (2024), Wu et al. (2024)	6
Problem-Solving	Hakim et al. (2024), Hanid et al. (2022a), Hanid et al. (2022b), Hwang, Lin, et al. (2023), Nadzri et al. (2024), Sudirman et al. (2022)	6
Memory Retention	Gargrish et al. (2022), Nadzri et al. (2023), Nadzri et al. (2024)	3

Challenges of AR Technology in Learning Geometry
Table 5 summarizes the three main challenges in implementing AR technology for learning geometry, based on the reviewed studies. Technical and resource limitations were evidenced in seven articles, while pedagogical barriers to using AR were also documented in seven articles. On the other hand, learner-related challenges were documented in four articles.

Table 5
Summary of the challenges of AR technology in learning geometry

Challenges	Authors	Frequency
Technical and Resource Limitations	Beisenbayeva et al. (2024), Gargrish et al. (2022), Koparan et al. (2023), Nadzeri et al. (2024), Tursynkulova and Madiyarov (2023), Yaniawati et al. (2023), Wu et al. (2024)	7
Pedagogical Barriers	Nadzeri et al. (2023), Nadzeri et al. (2024), Rohendi et al. (2025), Tarng et al. (2024), Tursynkulova and Madiyarov (2023), Yaniawati et al. (2023), Yanuarto et al. (2024)	7
Learner-Related Challenges	Hwang, Lin, et al. (2023), Na and Sung (2025), Nadzeri et al. (2023), Yaniawati et al. (2023)	4

Discussion
Based on the analysis, the publication trend from 2022 to March 2025 reflects a growing scholarly interest in exploring the use of AR technology in learning geometry, as evidenced by the consistent annual increase in article numbers. The predominant focus of these studies is on secondary school students, accounting for 14 out of the 31 reviewed articles. In contrast, other groups, such as elementary school students, high school students, teachers, and university students, receive more moderate attention. Therefore, these results suggest that AR is considered a tool with great potential to improve understanding of geometric concepts among young school students, possibly due to the suitability of this technology to their cognitive development level, as well as the need for innovation in mathematics teaching at this stage.

In terms of advantages, the analysis of the review indicates that AR significantly enhances achievement and learning outcomes in learning geometry. Students can use AR as a tool to learn geometry concepts (Hwang, Lin, et al., 2023; Pujiastuti and Haryadi, 2023a), improving their understanding effectively (Na and Sung, 2025), which is superior compared to students who do not use AR (Hanid et al., 2022a; Nadzri et al., 2023, 2024). This is because the AR feature provides enhanced instructional content (Hwang, Nurtantyana, et al., 2023; Tarng et al., 2024), including visual aids (Tursynkulova and Madiyarov, 2023), which help students understand the steps involved in formulating geometric concepts (Mandala et al., 2025). Moreover, by allowing direct manipulation of geometrical shapes, AR bridges conceptual gaps that often hinder students' comprehension when relying solely on static illustrations and diagrams, which are commonly used in conventional teaching settings. Additionally, AR provides effective scaffolding especially for average-achieving students (Beisenbayeva et al., 2024) and facilitates the guided learning of geometry concepts (Richardo et al., 2023). Thus, this enables students to repeat exercises, leading to improved learning outcomes (Nadzeri et al., 2023).

AR emerges as a powerful tool for enhancing students' visualization and spatial skills in geometry. Findings from empirical studies demonstrate that the use of AR enables students to achieve better visualization skills (Hanid et al., 2022a) and strengthens their spatial skills (Nadzeri et al., 2024; Wang et al., 2024). For instance, research by Sudirman et al. (2022) demonstrated that AR-integrated 3D geometry books help students construct and visualize shapes more effectively. Likewise, Yaniawati et al. (2023) reported that AR helps students visualize geometric objects clearly by providing useful features and animations. AR features enable students to view the world from a new perspective, allowing them to see inside the shape (Walkington et al., 2024) and providing a free 360-degree view, which enables them to observe from multiple angles (Singh et al., 2024). Thus, students can easily visualize and analyze the changes in surface area (Koparan et al., 2023) and visualize two-dimensional objects embedded within three-dimensional objects (Faizah et al., 2024). Furthermore, AR enables students to manipulate various virtual objects without the limitations of physical space (Mandala et al., 2025) and to observe the characteristics, length, size, and dimensions of geometric shapes that can be controlled within AR rather than relying on printed figures (Nadzri et al., 2023). These suggest that AR significantly enhances students' spatial skills by enabling dynamic and immersive visualization experiences that surpass the limitations of traditional instructional materials.

Additionally, empirical research also demonstrates that AR increases students' motivation and interest in learning geometry. Research by Pujiastuti and Haryadi (2023b) revealed that using hybrid learning with AR made geometry lessons more enjoyable and exciting, thereby enhancing students' motivation and interest. Similarly, Uriarte-Portillo et al. (2023) observed a positive motivational impact when students used an AR-enhanced Intelligent Tutoring System (ITS). On the other hand, research by Hakim et al. (2024) further emphasized that integrating AR into a printed learning module effectively motivated students to complete their learning tasks. The use of AR technology in learning promotes student motivation by helping learners grasp real-world concepts, build tangible models, and then apply these models to stimulate their interest (Yanuarto et al., 2024). As highlighted by Rohendi et al. (2025), the ability of AR to facilitate a dynamic learning environment and respond to user commands plays a vital role in sustaining student interest. Therefore, due to its interactive components and media elements, AR can create a better learning experience that supports students' motivation and attention towards learning.

Notably, AR also supports student-centered learning by bridging formal classroom instruction with real-world applications. This is exemplified by Hwang, Nurtantyana, et al. (2023), who developed an AR application that enables students to learn geometry in authentic contexts outside the classroom. In the same vein, Wu et al. (2024) developed AR picture books that facilitate independent reading through interaction with virtual content and real-time system responses. The interactive approach of AR provides hands-on experiences by enabling students to explore and examine geometrical shapes flexibly and connect them to real-life scenarios (Nadzeri et al., 2024). It also allows them to manipulate virtual shapes as if they were physical objects (Walkington et al., 2024). Moreover, AR facilitates personalized learning across diverse groups and enhances communication and collaboration (Koparan et al., 2023). This is supported by Nadzri et al. (2024), who established the collaborative implementation of an AR module, enabling students to interact with peers while using the technology. These findings underscore AR's capacity to foster both formal instruction and informal learning environments that encourage deeper understanding and meaningful collaboration in geometry education.

Another notable advantage of AR is its ability to develop students' problem-solving skills. Research by Hanid et al. (2022a) reported that students using AR demonstrated stronger computational thinking skills than those in the control group, implying that AR promotes structured approaches to problem-solving. Similarly, this aligns with Hakim et al. (2024), who discovered that learners using AR-integrated printed modules revealed greater improvement in mathematical problem-solving than those in conventional flipped classroom methods. This is because the use of AR technology can strengthen students' basic concepts, facilitating their ability to connect with formulas and solve problems at an advanced level. As reported by Nadzri et al. (2024), AR offers guided problem-solving support by allowing students to verify procedural calculations and receive answer suggestions provided on the devices. Additionally, Sudirman et al. (2022) determined that AR can minimize students' errors in understanding questions and solving problems by allowing direct interaction with geometric objects. Hence, these findings suggest that AR plays a crucial role in developing both conceptual and procedural problem-solving skills.

Previous research also demonstrates AR's capacity to improve the memory retention of geometric concepts substantially. A study by Gargrish et al. (2022) revealed that students who learned using AR had better memory retention compared to students in Interactive Simulation (IS) based learning groups. This finding is supported by Nadzri et al. (2023), who reported that students using AR applications demonstrated improved long-term memory retention of geometric concepts. Furthermore, this is supported by Nadzri et al. (2024), who observed that AR improves retention and fosters deeper conceptual understanding, which contributes to more durable memory consolidation. These findings collectively suggest that AR has the potential to reinforce both short and long-term learning outcomes through immersive and meaningful experiences.

Despite its numerous advantages, the use of AR technology in learning geometry also faces several challenges. One of its main challenges is technical and resource limitations. Gargrish et al. (2022) highlighted issues such as screen size and handling issues during learning. Additionally, the availability of suitable AR applications also influences their widespread adoption in teaching and learning. Thus, Nadzri et al. (2024) suggested that future researchers develop their own AR applications to ensure better suitability and align with the characteristics expected by the researcher. However, several studies have indicated that teachers face difficulties in designing and developing AR materials. Factors such as cost, limited coding knowledge, software compatibility, excessive work, and time constraints (Beisenbayeva et al., 2024; Koparan et al., 2023), as well as inadequate facilities and infrastructure constraints (Tursynkulova and Madiyarov, 2023; Yaniawati et al., 2023) are the primary contributors to this issue. Therefore, integrating AR with other supportive devices or applications based on existing resources could serve as an alternative approach to overcome this limitation, thus ensuring the effectiveness of its implementation across diverse learning environments.

Another challenge is pedagogical barriers, as the effectiveness of learning is fundamentally dependent on the pedagogical strategies employed by teachers (Tursynkulova and Madiyarov, 2023). Thus, pedagogical strategies are among the critical elements in the development and implementation of AR. As supported by Yanuarto et al. (2024), an effective teaching approach must be implemented in conjunction with the use of technology to maximize its benefit to students. Furthermore, Nadzeri et al. (2024) emphasized the importance of ensuring effective instructional design and the seamless integration of AR experiences into the curriculum. For instance, Tarng et al. (2024) revealed that AR does not necessarily enhance learning motivation, possibly due to the absence of sufficient gamification elements and overly formal instructional content. Nevertheless, teachers should realize that not all pedagogical strategies are compatible with every form of technology (Yaniawati et al., 2023). Therefore, Rohendi et al. (2025) established the importance of providing teachers with adequate training to integrate AR into their teaching practices effectively. Consequently, the integration of AR technology into geometry learning must be supported by appropriate pedagogical strategies and well-designed instructional approaches to maximize its impact on students.

The implementation of AR technology in geometry instruction also presents several learner-centered challenges that affect its effectiveness. Early adoption can be challenging for many students, as Hwang, Lin, et al. (2023) observed that students require additional time and training to use AR technology during its initial implementation. In addition, Na and Sung (2025) reported varied student engagement in using AR, with uneven participation in learning, as some students still avoided specific tasks. Therefore, it is important to consider the students' varying levels of knowledge and proficiency (Nadzeri et al., 2023). As indicated by Yaniawati et al. (2023), factors such as the level of understanding, learning styles, prior knowledge, and obstacles in using the application also contribute to students' difficulties in learning with AR technology. These findings suggest that a one-size-fits-all approach to AR implementation may not be effective, and student diversity must be considered when designing AR-supported learning environments.

Conclusion

This systematic review highlights the potential of AR in geometry education, underscoring its capacity to enhance achievement, visualization, spatial skills, motivation, problem-solving ability, and memory retention. Empirical evidence consistently demonstrates that AR supports deeper conceptual understanding by enabling dynamic interaction with geometric representations and bridging the gap between abstract concepts and tangible applications.

Additionally, AR's immersive features promote student-centered learning and strengthen students' motivation. However, the review also reveals challenges, including technical and resource limitations, pedagogical barriers, and learner-related issues that hinder the effective implementation of AR technology in learning geometry. Notably, the success of AR integration is closely linked to the use of appropriate instructional design and pedagogical strategies, as poor alignment can reduce its overall impact.

Based on the key findings of this review, several directions for future research are proposed. Future research should explore the long-term effects of AR integration in geometry learning across diverse educational levels and age groups, especially beyond the current focus on secondary students. Additionally, while existing studies provide encouraging evidence on conceptual understanding and problem-solving in learning geometry, more empirical work is needed to examine AR's influence on HOTS, such as creative and critical thinking, which are essential 21st-century competencies. Furthermore, research should also examine how AR can be effectively embedded within established pedagogical models in geometry education rather than viewing AR as a standalone intervention. Understanding how AR complements these models is crucial for designing effective instructional approaches that support active, student-centered learning. Moreover, further studies should investigate how AR can be combined with or integrated into other technologies to mitigate its limitations and enhance usability. Notably, to ensure consistent implementation, it is also important to develop standardized frameworks for evaluating the instructional design quality of AR-based learning tools. The lack of such standards has contributed to varied outcomes and limited the generalizability of research findings. In conclusion, AR presents a promising approach for enhancing geometry instruction by providing interactive, immersive, and engaging learning experiences. Hence, its continued development and thoughtful integration into teaching practice will be essential for supporting future-ready learners and advancing mathematics education in the digital age.

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