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Augmented and Virtual Reality Applications in K-12 STEM Education: Potentials, Limitations, and Future Directions

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Abstract

This study presents a systematic content analysis aimed at examining the effects of augmented reality (AR), virtual reality (VR), and mixed reality (MR) technologies on student achievement, motivation, engagement levels, and cognitive gains within the context of STEM (Science, Technology, Engineering, and Mathematics) education. A total of 59 peer-reviewed academic articles published between January 2019 and June 2024 were systematically reviewed using an article analysis form developed by the researchers. Throughout the review process, multiple variables were examined, including the journals in which the studies were published, year of publication, types of technology used (AR/VR/MR), country of implementation, research methods and design types, participant age/grade levels, sample sizes, discipline areas (STEM, Mathematics, Science, etc.), sub-domains, problem focus, and the significance of research findings. In addition, the keywords used in each study, the number of citations, and the Q-index classifications of the journals were also analysed in detail. The findings indicate that AR and VR-based applications significantly enhance students' academic performance, attitudes toward courses, and levels of participation compared to traditional instructional methods. Furthermore, certain implementations have been shown to positively impact learners' scientific process skills, problem-solving strategies, and self-regulation abilities. These results reveal the strong pedagogical potential of integrating digital technologies into learning environments and offer meaningful implications for instructional designers, educational technology practitioners, and policymakers.

Keywords Augmented reality · Virtual reality · Mixed reality · STEM education · Content analysis · Digital education · Systematic review

Introduction

The digital transformation experienced in educational technologies has prompted a reshaping of instructional methods, and the application of augmented reality (AR), virtual reality (VR), and mixed reality (MR) technologies, particularly within the context of STEM (Science, Technology, Engineering, and Mathematics) education, has emerged as a significant field of research. These technologies enhance learning environments, making them more interactive and experiential, thereby deepening students' conceptual understanding and increasing their motivation to learn (Zhang et al., 2024).

Recent studies indicate that the integration of extended reality (XR) technologies into STEM education has positive effects on students' achievement, self-regulation skills, and cognitive development (Ramli et al., 2023). The affordances of AR/VR-supported systems, particularly in terms of concretisation, active participation in learning materials, and personalised learning, are noteworthy (Zhang & Wang, 2021). The integration of these technologies is not confined to student academic outcomes; it also brings about significant changes in instructional design, classroom management, and pedagogical practices (Chin et al., 2024). For instance, applications supported by virtual and augmented reality contribute to the proliferation of interactive and collaborative learning environments where students assume more active roles (Lee et al., 2022; Jiang et al., 2025). A bibliometric analysis conducted by Dogru et al. (2025)

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supports the growing interest in AR technologies within STEM education, noting the thematic diversification and expansion of international collaboration networks in recent publications.

This technological advancement is highlighted as being influential not only on individual learning but also on the social learning and pedagogical context. A comprehensive content analysis by Fernández-Cerero et al. (2024) examines the educational potential of (XR) technologies from various dimensions, stating that these technologies do not merely offer technical innovations but also provide inclusive, motivating, and pedagogically rich learning environments. The study notes that whilst the application areas of XR in education are expanding, there remains a need for greater contextual, pedagogical, and methodological depth.

Furthermore, with the integration of artificial intelligence, gamification, and mobile technologies into AR/VR environments, it is observed that learning experiences are becoming more personalised, and student interest is sustained (Lampropoulos, 2025). Mobile applications developed in this context enable users to participate in learning processes independent of location and time, thereby supporting the continuity of learning (Dong et al., 2024).

In this new paradigm where educational content is digitalised, AR-supported intelligent tutoring systems developed to include learners with disabilities contribute to the principle of inclusive education (Ahuja et al., 2022). Moreover, meta-analysis findings evaluating the impact of augmented reality applications in STEM education demonstrate that these technologies are effective tools in terms of learning outcomes (Wang et al., 2024).

However, to understand the educational impacts of these technologies in a multidimensional manner and to systematically analyse the trends in the existing literature, there is a need for holistic and comprehensive studies. Although numerous systematic reviews and meta-analyses have examined the effects of AR and VR technologies in education over the past decade (e.g., Hidayat & Wardat, 2024; Wang et al., 2024; Zhang & Wang, 2021), most of these studies have either focused on single technology types (AR or VR) or have included broad educational contexts such as higher education and informal learning environments. Moreover, few studies have conducted a comprehensive content analysis specifically addressing K–12 STEM education that simultaneously compares AR, VR, MR, and XR technologies within the same analytical framework. Therefore, this study aims to fill this specific gap by providing a multidimensional examination of how these immersive technologies have been implemented in K–12 STEM education between January 2019 and June 2024, identifying trends, methodological patterns, and pedagogical implications that have not been synthesised collectively in previous research. In this regard, it is of great importance to reveal different perspectives in the field, to analyse the methodological diversity, and to more clearly establish the relationship between pedagogical outcomes and technology (Kefalis et al., 2025).

Methodology

Research Design

Within the scope of this study, 59 academic articles published between January 2019 and June 2024 were examined using the content analysis method. During the analysis process, the "Article Publication Classification Form" developed by Goktaş et al. (2012) was adopted as a foundation, but it was updated in accordance with the study's objectives. In this context, various variables were analysed, such as the year of publication, the journal of publication, the type of technology used (AR/VR/MR), the country where the study was conducted, the research method and design type, participant characteristics, sample size, domain and sub-domain, problem focus, the significance of the results, keywords, and Q-index classifications.

This study aims not only to describe the existing literature but also to analyse the effects of technology-supported instructional applications in a multidimensional manner, thereby contributing to areas such as instructional design, policy development, and practitioner guidance. In the current era of rapidly advancing educational technologies, such systematic content analyses not only contribute to the body of literature but also provide a scientific foundation for the dissemination of innovative pedagogical approaches.

This study utilized a systematic content analysis approach to investigate how Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR) technologies have been implemented in K–12 STEM education between January 2019 and June 2024. A structured article review form was developed by the researchers based on the classification framework proposed by Goktaş et al. (2012), allowing for the multidimensional examination of selected publications. The coding form was designed to capture variables related to technology type, research method and design, participant characteristics, educational domain, and learning outcomes.

In line with the purpose of this systematic content analysis, the study was guided by the following research questions:

(1) To what extent and in what forms have AR, VR, MR, and XR technologies been integrated into K–12 STEM education between January 2019 and June 2024?

(2) What research methodologies, design approaches, and participant characteristics have characterised the empirical studies conducted in this field?
(3) Which learning outcomes, cognitive or affective effects, and pedagogical implications have been most frequently identified and reported in the reviewed literature?
(4) What publication trends, disciplinary focuses, and methodological patterns can be discerned across years, journals, and countries represented in the corpus?

To ensure transparency and replicability in the study selection process, the PRISMA guidelines (Moher et al., 2009; 2010) were followed. As illustrated in Fig. 1, the process involved four systematic steps: identification, screening, eligibility assessment, and final inclusion.

Inclusion Criteria and Sample

The peer-reviewed articles in the literature review fulfil the following criteria:

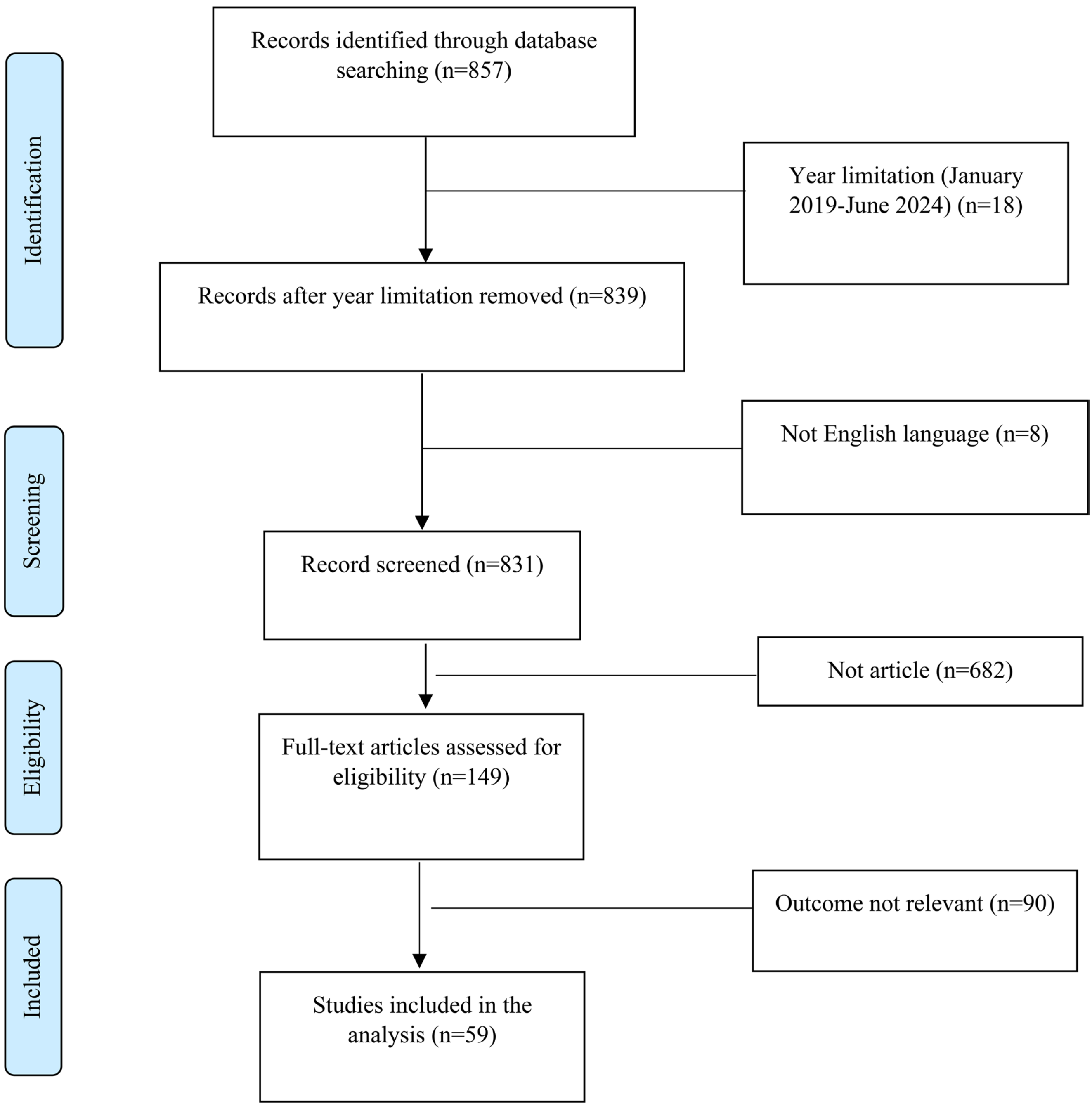


Fig. 1 PRISMA Flow Chart for Sourcing

- The paper must be published in the years ranging from January 2019 to June 2024.

Accordingly, the 'Year limitation' step in the PRISMA flow chart indicates the removal of studies falling outside this predefined period, functioning as an initial filtering criterion based on publication date.

- Articles that report an approach for implementation.
- Contents of the paper provide satisfactory details for the selected topics.
- Language of the article should be English.
- Only primary studies were selected, and duplicate records were removed.
- The selected articles provide sound knowledge from the research questions formulated.
- The article must be from the selected digital repositories.
- K12 grades, from primary school to high school.

Exclusion criteria:

- The papers not in the range of January 2019 to June 2024.
- Gray papers – Theses, conference proceedings, book chapters, etc.
- Duplicate versions.
- Provides no information for the research questions selected.
- Written in other than English language.
- Preschool, undergraduate or graduate levels.
- Meta-analysis, SLR, review articles or editorials.
- Studies in which only teachers participated.

Conducting searches across all fields aims to provide a thorough understanding of the research and identify peer-reviewed publications that align with the study's overall purpose.

Databases are utilized for the following reasons:

- Comprehensive Database: The selected databases cover a wide array of scientific disciplines, enabling researchers to access crucial scientific publications across various fields.
- Citation Tracking and Analysis: They offer citation information, showing how frequently a publication is referenced in other works. This aspect is valuable for gauging the impact and importance of research. Citation analysis assists researchers in assessing the impact of their work and spotting research trends.
- Standardized Data: Data is presented in a standardized manner, allowing researchers to easily compare and analyse data from diverse studies.
- Reliability: They prioritize high-quality and dependable scientific publications, establishing it as a reputable resource for researchers.

These criteria were applied to ensure a coherent and methodologically consistent sample that reflects the core research focus. The selection process was conducted using comprehensive database search guided by the search strategy illustrated in Fig. 1 and summarized in Table 1.

The 'Year limitation' step reflects the exclusion of studies published outside the predefined timeframe (January 2019–June 2024). Articles published before 2019 or after June 2024 were removed at this stage of the screening process.

Data Collection and Analysis Procedures

The data collection process was conducted through systematic search queries applied across four major academic databases: Web of Science, Scopus, Google Scholar, and dblp. The search was designed to retrieve empirical studies published between January 2019 and June 2024 that addressed the integration of Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR) technologies in K–12 STEM education. The Boolean search string employed a combination of technological, educational, and methodological terms. The full query and scope of the research corpus are summarized in Table 1.

This systematic query facilitated the identification of relevant peer-reviewed articles aligned with the educational applications of AR, VR, and MR technologies. Each article was reviewed using the structured coding form described in the Research Design section. The form included the following variables:

- Year of publication
- Type of technology (AR, VR, MR)
- Country of study
- Research method and design
- Participant age or grade level
- Sample size

Table 1 Information on the research corpus and search queries adopted for the inclusion criteria

Research Corpus	
Databases	Web of Science, Scopus, Google Scholar, dblp
Period	January 2019-June 2024
Search Queries	("metaverse" OR "virtual reality" OR "augmented reality" OR "mixed reality" OR "extended reality" OR "immersive" OR "spatial") AND ("school*" OR "teach*" OR "education" OR "learn*") AND ("k-12" OR "k12" OR "k 12") AND ("STEM" OR "STEAM") AND ("experimental" AND ("control" OR "comparison"))

- Educational domain and sub-domain (e.g., science, math, engineering).
- Problem area (e.g., motivation, engagement, achievement).
- Q-category of the publishing journal.
- Citation count.
- Significance of reported results.

Because AR, VR, and MR terminology are not used consistently across the literature, each study was coded according to the technological characteristics described (e.g., immersion level, device type, interaction mode) rather than relying solely on the terminology chosen by the authors. In a few cases where the authors mislabeled technologies, classification was corrected during coding to maintain consistency with our operational definitions. The data were analysed both descriptively (e.g., frequency counts) and thematically to explore dominant trends, gaps, and methodological tendencies in the literature.

Strengths and Limitations

A notable strength of this study is its adoption of a structured, multidimensional systematic content analysis approach, configured to examine the use of augmented reality (AR), virtual reality (VR), and mixed reality (MR) technologies within the context of STEM education. The 59 peer-reviewed articles examined in the study were analysed using a review form, updated by the researchers, based on the classification framework developed by Goktaş et al. (2012). This method ensured that the data were handled in a transparent, replicable, and comparable manner, which facilitated the identification of thematic patterns among the variables. The resulting findings comprehensively present the current trends concerning the application of AR, VR, and MR technologies in K-12 STEM education, the preferred methodological approaches, and the variations in pedagogical outcomes.

Nevertheless, certain limitations must be acknowledged. Firstly, the inclusion was restricted to studies published in the English language, which may have led to the exclusion of qualified publications in other languages. Secondly, although comprehensive databases such as Web of Science, Scopus, Google Scholar, and dblp were utilised, these sources may not have covered all relevant publications. This situation could limit the generalisability of the study's findings. Thirdly, the analysis was confined to descriptive and thematic techniques; more advanced data mining methods (e.g., t-SNE, PCA) or bibliometric network analyses were not applied. The absence of these techniques may have restricted the identification of deeper structural patterns.

Notwithstanding these limitations, the study makes a significant contribution to the literature on the integration of augmented, virtual, and mixed reality technologies into K-12 STEM education; it also provides a solid foundation for future experimental and meta-analytic studies.

Findings and Discussions

Within the scope of this study, a total of 59 academic articles published between January 2019 and June 2024 were examined, and the effects of augmented reality (AR), virtual reality (VR), and mixed reality (MR) technologies within the context of STEM education were analysed from a multidimensional perspective. The findings indicate a literature that is rich and diverse in both content and methodology.

Frequency Distribution by Year

When the frequency distribution by year is examined, 2020 emerges as the period with the highest number of publications, totalling 15 articles. This year is followed by 2019 ($n=12$), 2021 ($n=11$), 2022 ($n=10$), and 2023 ($n=10$), respectively. Only one study from 2024 is included (Fig. 2). The considerably low number of publications for 2024, despite the comprehensive search conducted up to June 2024, suggests that research interest may be shifting from this area towards different technological themes.

This distribution reveals a significant surge in the number of publications in 2020, particularly influenced by the COVID-19 pandemic, which rapidly increased interest in digital education technologies. The pandemic led to the widespread adoption of remote learning, virtual learning environments, and technology-supported instructional practices; in parallel, research interest shifted towards augmented/virtual reality technologies. The year 2020 can be considered a turning point for the use of AR/VR applications in education. The year 2019 was a period when seminal studies on the pedagogical potential of AR/VR technologies were produced (e.g., Chen, 2019; Makransky & Mayer, 2019; Sahin & Yılmaz, 2020), and these technologies began to be systematically included in the research agenda. This year also includes the first instances where technological innovations were experimentally investigated within an educational context.

Between 2021 and 2023, a relatively balanced distribution in the number of publications is observed. This period reflects a transition phase where technology-based teaching approaches were adopted at an institutional level in the post-pandemic era, and innovative applications in instructional design became permanent. The studies published in 2021,

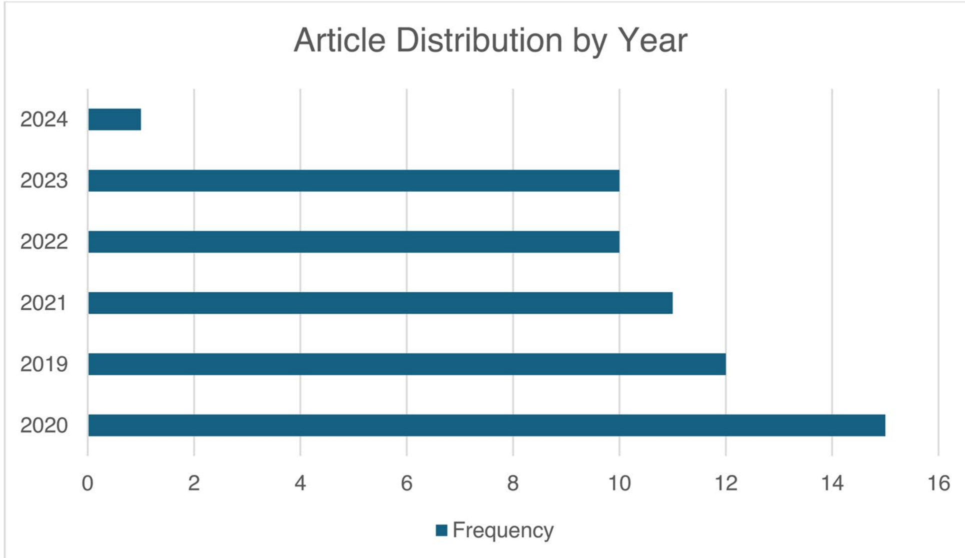


Fig. 2 Distribution of articles by year

in particular, show a diversification in both experimental designs and case-based applications. The low publication count for 2024 suggests that these technologies have reached a relative saturation point in the literature, and academic interest is now shifting towards more current themes such as artificial intelligence, learning analytics, or data-driven personalisation.

In conclusion, the analysis by publication year indicates that educational research based on AR/VR gained momentum in 2019, peaked in 2020, and continued in subsequent years with more systematic, institutional, and methodologically diverse studies. This trend clearly demonstrates that the integration of technological innovations into learning processes is no longer a temporary trend but has become a permanent research agenda.

Publisher Frequency Distribution

When the publishers of the journals in which the articles were published are analysed, it is observed that the publications are concentrated in certain major publishing houses (Fig. 3).

According to the frequency distribution, the publisher with the highest number of publications is Springer ($n=13$). Springer is followed by Taylor & Francis ($n=8$), Elsevier ($n=8$), and Wiley ($n=7$), respectively. These four major publishers shape the literature in the fields of educational technology and interdisciplinary STEM research, with both their extensive journal portfolios and high-impact factor publications. Furthermore, MDPI, a prominent representative of open-access publishing, is a noteworthy publisher in

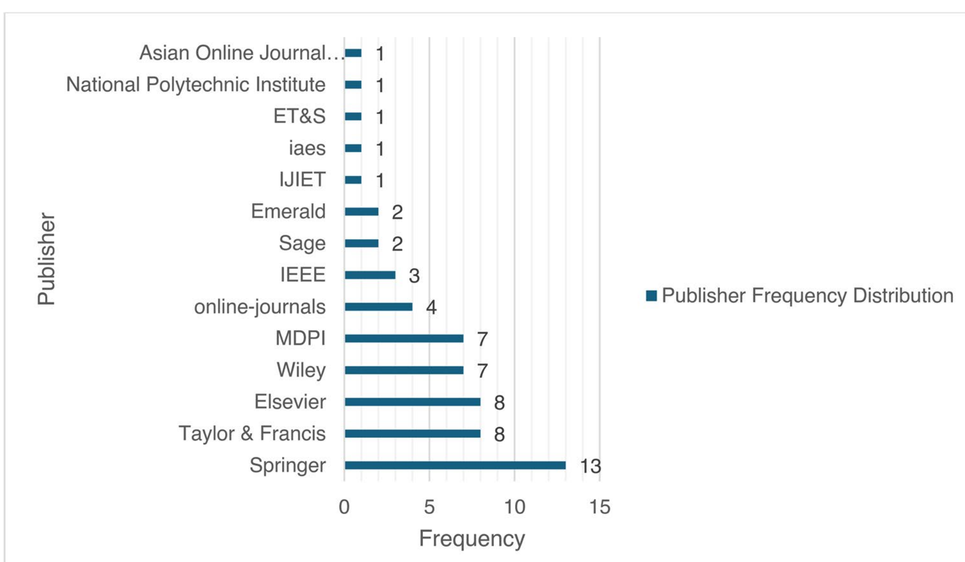


Fig. 3 Frequency Distribution of Publishers

the analysis, with a total of 7 publications. The increasing visibility of MDPI reflects the impact of open-access policies and rapid publication processes on the academic world in recent years.

While IEEE ($n=3$) stands out with its more technical and engineering-focused publications, publishers such as SAGE ($n=2$) and Emerald ($n=2$) have also contributed with a limited number of high-quality publications. Apart from these, publishers such as Online-Journals ($n=4$), ET&S, IJIET, IAES, Asian Online Journal Publishing, and the National Polytechnic Institute are represented at the level of individual studies. This distribution shows that scientific output in the field is largely shaped by global publishers, while also indicating a significant contribution from open-access platforms. This diversity among publishers reveals that augmented and virtual reality technologies are widely investigated in both education- and technology-focused disciplines, and that interdisciplinary interaction is strengthening.

Journal Frequency Distribution

The distribution of publications by journal reveals the academic platforms where research is most intensely published (Fig. 4). According to the frequency analysis, the journal that hosted the most publications was Interactive Learning Environments ($n=6$). This journal provides a strong publication outlet for interdisciplinary research on the educational effects of augmented and virtual reality applications.

Interactive Learning Environments is followed by the British Journal of Educational Technology ($n=5$), Mathematics ($n=3$), Education and Information Technologies ($n=3$), and the International Journal of Emerging Technologies in Learning ($n=3$). These journals focus on academic studies investigating how augmented and virtual reality applications are used in educational contexts, particularly in the fields of STEM, mathematics, and science.

Furthermore, journals such as the Journal of Educational Computing Research ($n=2$), the Journal of Computer Assisted Learning ($n=2$), Computers & Education ($n=2$), and Virtual Reality ($n=2$) are also prominent publication sources. These journals tend to focus on topics such as technology-supported learning, cognitive load, user experience, and virtual learning environments.

The remaining 31 journals are each represented by a single study. This situation indicates that the research topic is spread across various academic platforms and highlights its multidisciplinary nature. For example, journals such as Computers in Human Behavior, IEEE Transactions on Learning Technologies, Educational Technology & Society, F1000Research, and Library Hi Tech host high-quality publications that build bridges between fields like education, technology, cognitive science, and computer engineering. This broad distribution shows that AR/VR technologies find relevance not only in the education sciences literature but also in the fields of engineering, computer science, and learning sciences. Moreover, the frequent preference for journals in the Q1 and Q2 categories supports the high scientific impact level of the research included in the studies. The frequency distribution of journals that published at least two articles in the field is presented in Fig. 4.

Q Category Frequency Distribution

The classification of journals in which the articles were published according to Q (quartile) categories is an important indicator for revealing the scientific impact level of the studies. The Q category distributions are presented in Fig. 5.

Fig. 4 Frequency Distribution of Articles by Journal

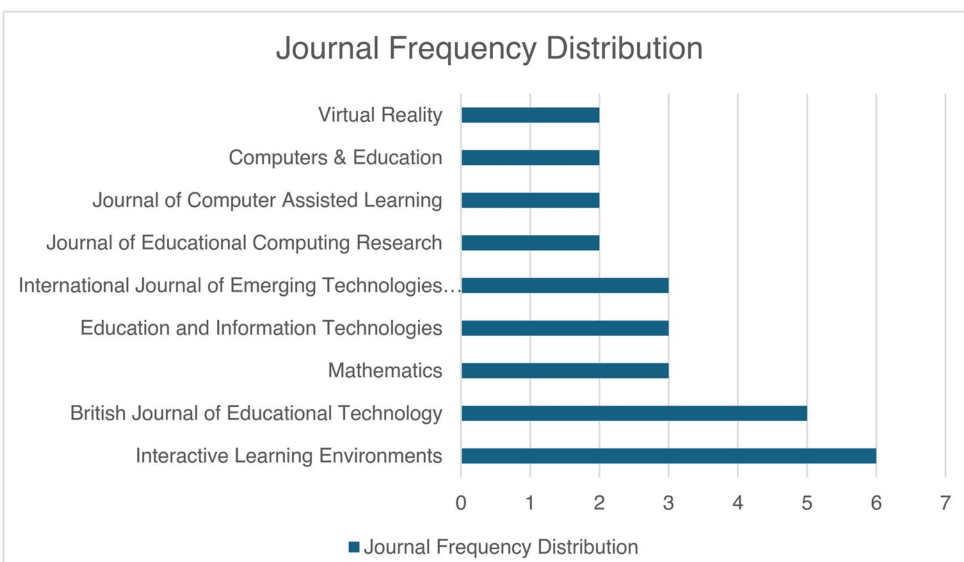
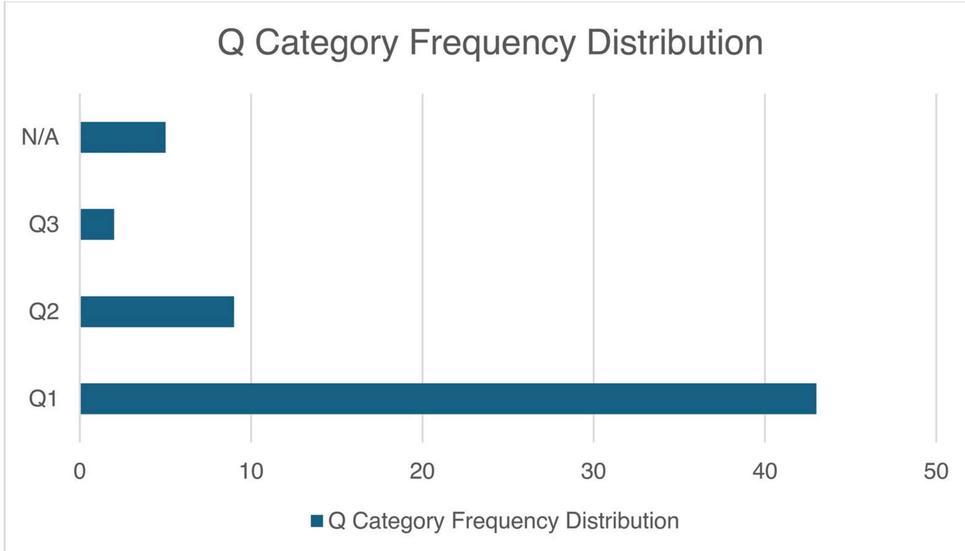


Fig. 5 Q Category Frequency Distribution



The Q categories, determined by international citation indices such as Scopus and Web of Science, indicate the relative rankings of journals within their respective fields. In this context, Q1 represents the top 25% percentile; Q2 and Q3 represent the middle level, while N/A indicates journals that are not indexed or classified. According to the frequency distribution, the number of articles published in journals in the Q1 category is 43. This number corresponds to 73% of the total publications. This finding shows that the vast majority of the studies included in the analysis were published in journals with high impact factors and strong academic reputations in their fields. The number of articles in the Q2 category is 9. These journals also have high visibility and are among the reputable platforms where research on educational technologies and interdisciplinary studies is published. Only 2 articles are in the Q3 category, which shows that publications in journals with a relatively lower impact factor are quite limited. In the N/A (Not Available) category, meaning journals without any Q classification, there are 5 articles. These journals are generally either very new and not yet indexed, or they are part of alternative open-access platforms.

Overall, 88% (n=52) of the total publications were published in Q1 or Q2 category journals. This situation demonstrates that the studies on the effects of augmented and virtual reality technologies in the field of education provide strong academic outputs not only quantitatively but also qualitatively. This trend in the literature clearly indicates that the relevant themes are at the centre of high-impact scientific discussions.

Frequency Distribution of Citations on the Article

When the citation counts for the analysed articles are examined, significant findings regarding the scientific impact level and visibility of the research in the literature have been obtained. While the journals in which the articles are published are concentrated in the Q1 and Q2 categories, many have also received a high number of citations. According to the frequency distribution, citation counts vary over a wide range, from 0 to 387.

According to the data, there are 45 articles with 10 or more citations. This shows that a large portion of the reviewed literature is actively referenced in the field. The most cited study is the article titled "The effect of Augmented Reality Technology on middle school students' achievements and attitudes towards science education" published by Sahin & Yilmaz (2020) in *Computers & Education*. With 387 citations, this study holds a pioneering position in the literature. Sahin and Yilmaz are followed, respectively, by the study titled "Impact of augmented reality technology on academic achievement and motivation of students from public and private Mexican schools" (219 citations) by Ibáñez, M. B., et al. (2020), also published in *Computers & Education*, and the study "Effect of Mobile Augmented Reality on Learning Performance, Motivation, and Math Anxiety in a Math Course" (196 citations) by Chen (2019) published in the *Journal of Educational Computing Research*.

In total, 12 articles have received 100 or more citations. This high level of citation indicates that the relevant studies are among the fundamental references in the field. The number of articles with 50 or more citations is 26, which demonstrates that STEM education and AR/VR applications are not just a research topic but also have a high impact in terms of academic productivity. In contrast, 12 articles with fewer than 10 citations were identified in the analysis. Notably, articles with 2 and 3 citations were repeated four times each, and there were also two studies with 0 citations. Such publications are often either recently published or appear in journals with limited access.

This distribution reveals that the scientific impact of publications varies depending not only on the Q classification of the journal in which they are published but also on various factors such as the choice of topic, research methodology, level of innovation, and accessibility. For example, some studies from the post-pandemic period may receive high citations in a short time, while some high-quality studies may not yet have achieved sufficient visibility.

In conclusion, from the perspective of citation distribution, the analysed literature includes both high-impact studies and emerging publications that provide new contributions. This situation indicates that research in the field of augmented and virtual reality technologies in education has both an established foundation and a dynamic structure open to new opportunities.

Method Frequency Distribution

When the research methods of the analysed articles are examined, it is seen that the vast majority of studies were conducted using quantitative methods (Fig. 6).

According to the frequency distribution: 35 studies were quantitative, 21 were mixed methods, and only 3 were qualitative. This distribution shows that in research examining the educational effects of AR/VR applications, designs based on experimental and measurable data are prominent. In quantitative studies, pre-test/post-test control group designs, single-group experimental designs, correlational studies, and comparisons based on statistical analysis were frequently used. Such studies are particularly aimed at testing the effects of AR/VR technologies on variables such as student achievement, motivation, cognitive load, self-regulation, and engagement.

On the other hand, the number of mixed-methods studies is also quite high ($n=21$). This indicates that researchers adopt comprehensive data collection strategies to both reveal measurable effects with statistical data and to make sense of participant experiences, perceptions, and in-process observations. In mixed-methods research, an approach of providing explanatory depth to quantitative findings with qualitative data is generally adopted.

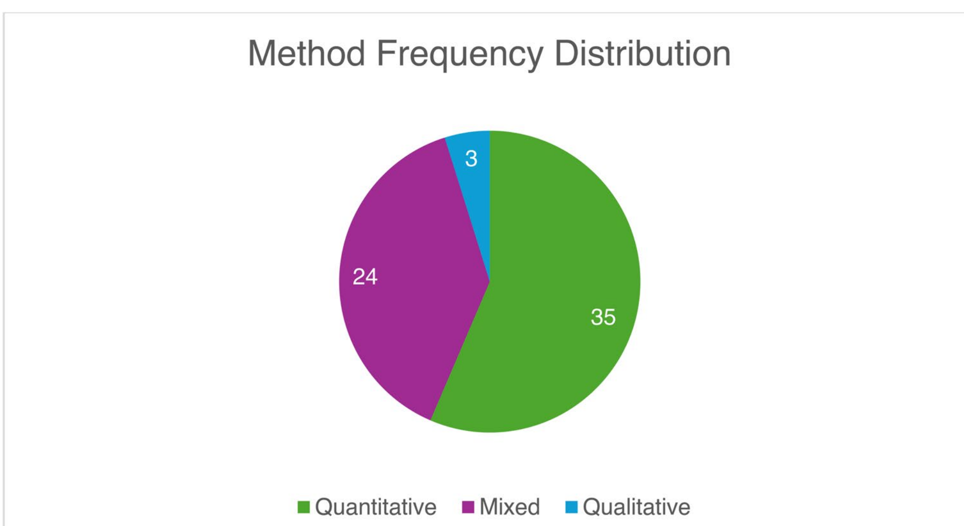
The number of studies conducted with a qualitative method is only 3. This low rate suggests that research in the field is still more focused on experimental and measurable results, with the qualitative perspective remaining limited. However, qualitative research is important for a deeper understanding of student experiences, teacher perceptions, and the opportunities and limitations within the implementation process. In this context, increasing academic interest in qualitative approaches presents a significant opportunity to evaluate the pedagogical dimensions of AR/VR applications more comprehensively.

Design/Approach Frequency Distribution

When the research approaches are examined, it is seen that experimental designs are clearly dominant (Fig. 7).

According to the frequency distribution: Experimental designs were used 50 times, case studies 3 times, and a mixed approach was preferred twice. Grounded theory, event-related response & mixed block, action research, and multimodal analysis were each used once. These findings show that augmented and virtual reality applications in educational settings are generally investigated with an effect-analysis focus, using experimental designs such as pre-test/post-test control group comparisons. Experimental designs are mostly structured to measure the effects of AR/VR applications on outcomes such as students' academic achievement, motivation, self-efficacy, and participation. This also reveals the prominence of the effort to establish causal relationships in the literature.

Fig. 6 Method Distribution



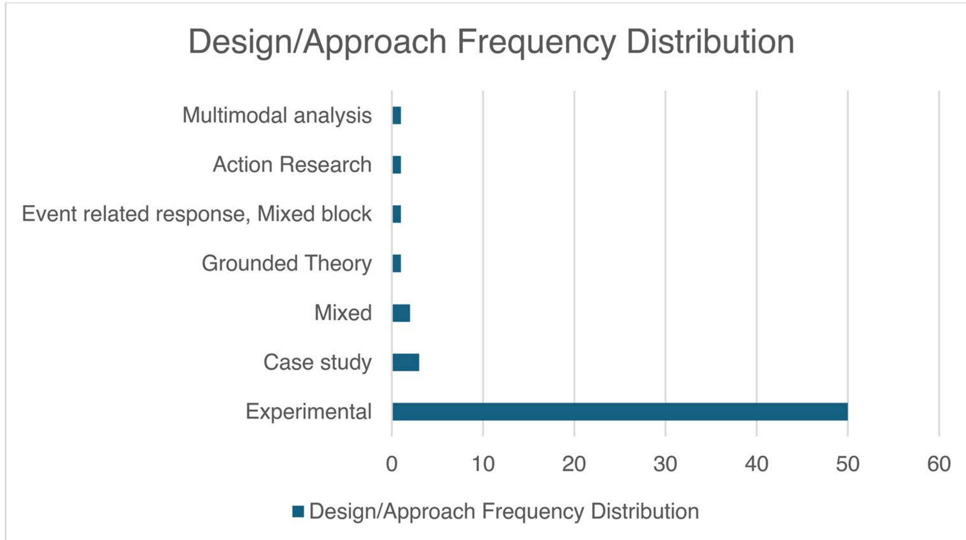


Fig. 7 Design/Approach Frequency Distribution

In addition, a case study design was used in only 3 studies. These designs are generally aimed at a deep understanding of classroom applications, teacher-student interactions, or a specific implementation process. However, their small number indicates that research conducting process evaluations with qualitative data is still limited. Mixed designs ($n = 2$), represent approaches that integrate both quantitative and qualitative methods. These studies generally aimed to address the pedagogical dimensions of an application from a broader perspective by supporting an experimental process with qualitative observations. On the other hand, singular examples such as Grounded Theory ($n = 1$), Event-related response and mixed block design ($n = 1$), Action Research ($n = 1$), and Multimodal Analysis ($n = 1$) indicate the existence of alternative and innovative methodological approaches in the literature. However, the limited number of these designs shows that the experimental tradition still dominates AR/VR research.

Domain Frequency Distribution

In the analysis of the disciplines on which the 59 articles focused, it is observed that the studies are, as expected, largely positioned within the STEM (Science, Technology, Engineering, Mathematics) framework. This is followed by 12 articles in mathematics, 10 articles in science, and 1 article in STEAM (Fig. 8).

These findings show that augmented (AR) and virtual reality (VR) applications are most intensively used in multidisciplinary learning approaches, especially in STEM-focused content. Studies within the STEM framework generally aimed to develop students' 21st-century skills by integrating areas such as mathematics, science, and engineering design. Studies in the field of mathematics ($n = 12$) generally focused on outcomes such as geometric concepts, spatial intelligence, problem-solving skills, and mathematical achievement. In most of these studies, the supporting role of AR/VR technologies in processes such as concretisation, visualisation, and interactive learning was emphasised. Studies within the scope of science ($n = 10$) were concentrated in sub-fields such as physics, biology, and environmental education. These studies were directed towards goals such as increasing students' understanding of abstract concepts, simulating experimental processes, and developing scientific process skills.

Only one study was conducted with a STEAM (including Arts) approach. This indicates that art-focused content has yet to find a significant place in AR/VR-supported educational research. However, the STEAM approach, with its potential to integrate aesthetics, creativity, and expressive skills with technology, could be a noteworthy direction for future researchers. In general, this distribution shows that the most common application areas of AR/VR-based applications are shaped around the STEM axis, and the pedagogical integration, especially in the context of mathematics and science education, is strong.

Sub-domain Frequency Distribution

The sub-domains of the disciplines addressed reveal which subject contents augmented, and virtual reality applications have concentrated on. According to the frequency distribution, the most frequently focused sub-domains were science, geometry, and physics, which are cognitively challenging and open to visualisation. The analysis revealed that the most frequently encountered sub-domains were Science (f = 10), Geometry (f = 9), Physics (f = 4), STEM (f = 4), and Science and Technology (f = 4). It can be said that these sub-domains were predominantly preferred and investigated within the scope of the study. Additionally, Biology and Math sub-domains appeared with a frequency of 3 each.

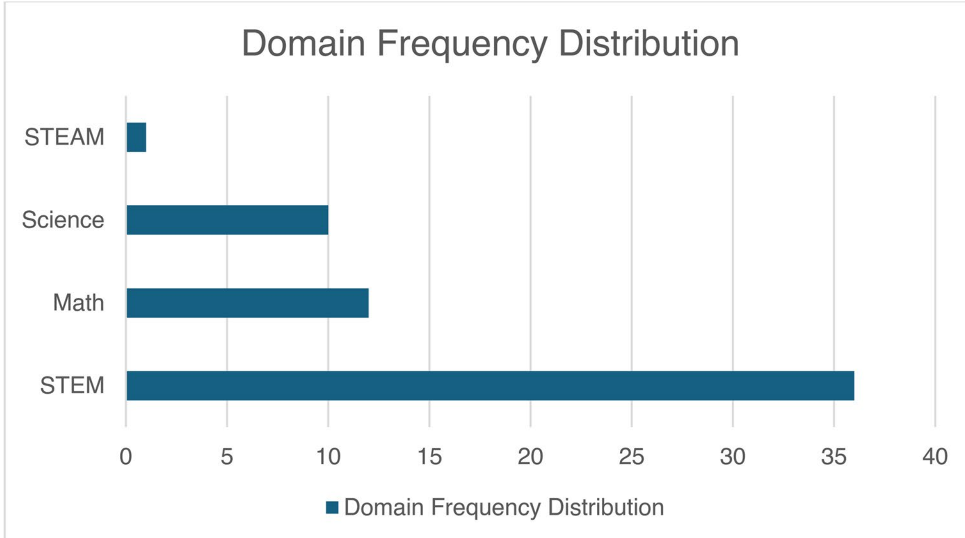


Fig. 8 Domain Frequency Distribution

On the other hand, it is understood that categories such as Math and Engineering, Probability, Programming, Earth and Universe, Physics-Mathematics, Problems, Fractions, Engineering, Plants, Cell, Environmental Science, Science and Engineering, Planetary Science, Geography, Leverage, Animals and Plants, Electrochemical Cells, Earth and Moon, Maker, Robotics, and Art were each preferred only once. These findings, while revealing a concentration of studies on sub-domains like Science and Geometry, also show that other sub-domains were addressed more limitedly. These results indicate that within the scope of the study, there is a focus on fundamental disciplines such as Science, Geometry, and Physics, while other disciplines are examined much more specifically and limitedly.

Problem Area Frequency Distribution

The problem areas addressed reflect the fundamental issues that augmented reality (AR) and virtual reality (VR) applications aim to solve in the context of education. According to the frequency analysis results, the majority of studies focused on learning outcomes such as student achievement, motivation, engagement, and self-efficacy.

The analysis revealed that the most frequently encountered problem was Academic Achievement (f=28). This indicates a strong trend towards testing the effect of augmented and virtual reality applications on students' achievement levels. This area is followed by: the Motivation and Interest theme (Motivation, Enjoyment, Intrinsic Motivation, Learning Motivation, total f=11), the Engagement and Interaction theme (Engagement, Student Engagement, Emotional Engagement, total f=10), and the Self-Efficacy theme (Self-efficacy, Academic self-efficacy, Science self-efficacy, total f=7). These themes address the affective and behavioural tendencies of students in the learning process, demonstrating that AR/VR applications are studied not only for their cognitive but also for their affective impact dimensions.

Among other moderately encountered problem areas are: the Attitude and perception theme (Attitude, Attitudes towards science education, Attitude for AR, Views of science, total f=7), the Usability and technology acceptance theme (Usability, System usability, Technology acceptance, total f=6), and the Cognitive load and mental processes theme (Cognitive load, Cognitive demand, Critical thinking, total f=5). These themes show that students' perceptions of technology, system experiences, and cognitive capacities hold a significant place in research. The remaining problem areas have been studied mostly once and exhibit significant thematic diversity. These include various concepts such as collaboration, metacognitive tendency, epistemic curiosity, spatial intelligence, game engagement, AI learning activity, imagination skills, immersive experience, judgment, prediction and explanation; demonstrating that AR/VR applications have a multifaceted and open-to-exploration structure.

These findings, while revealing a research trend that AR/VR technologies are effective on key outputs in education, especially academic achievement, motivation, engagement, and self-efficacy, also show that original and innovative problem areas are still being addressed to a limited extent. This situation reveals a need for future studies to address cognitive, affective, and social impact dimensions in a more holistic manner.

K12 Grade (or yo = years old) Frequency Distribution

The analysis of participant profiles indicates that the majority of the studies were conducted with K12 level students, i.e., from primary school to the final year of secondary school. In this context, the frequency analysis, taking into account both grade levels and age ranges (years old), shows which student levels the research has focused on. The age groups preferred at least twice are presented in Table 2.

When participant profiles are evaluated, it is seen that the studies were conducted with K12 level students in line with the research framework. In particular, the middle school level stands out as a prominent application area for augmented and virtual reality (AR/VR) technologies. Students at this level present a suitable profile for such innovative learning environments, both in terms of their cognitive development levels and their capacity for technology adaptation.

According to the frequency analysis, the most frequently encountered grade level is 6th grade (f=8), followed by 7th grade (f=6) and 5th grade (f=5). These grades are followed by the 13–15 years old age range (f=3), 4th grade (f=3), 10th, 11th, and 3rd grade (each f=2), as well as 9th grade and the 8–9 years old group (f=2). These findings indicate the dominance of middle school applications in the literature. In age-based classifications, the 13–15 years old range (f=3) is the most frequent group. It is noteworthy that this age group represents the middle school level and is a favourable period for interaction with technology. Other age ranges are mostly represented by single instances. Among these are broader or narrowly defined age groups such as "9–11 years", "11–15 years", "14–16 years", "14–17 years", "16–18 years". Furthermore, grade levels defined with general categories such as "Upper Secondary", "Middle", "High" were each reported only once. This situation shows that in some studies, the grade level was not precisely specified or that there were conceptual ambiguities. It was also observed that sample groups indicating the early childhood period (e.g., "1–2 years", "6–7 years") were included in only a few studies.

In general, these findings show that educational research on AR/VR technologies has focused on middle school and, to some extent, high school students, while primary school, early childhood, and adult learners have been studied more limitedly. Furthermore, the occasional use of non-standardised expressions in grade and age level definitions complicates comparative analyses. This situation highlights the necessity for more systematic and consistent reporting of age-grade level pairings in future studies.

Table 2 Frequency Distribution of K12 Grade (or yo=years old)

K12 Grade (or yo=years old)	Frequency
6	8
7	6
5	5
13–15 yo	3
4	3
10	2
11	2
3	2
8–9 yo	2
9	2

Sample Size Frequency Distribution

Sample sizes provide important clues about the scope of the studies, data collection methods, and research designs. According to the frequency analysis results, there is no clear standardisation in sample sizes, and a wide range of values are used in different studies.

The most frequently encountered sample size is 30 participants (f=3), followed by values such as 66, 75, 82, 90, 102, 40, and 44 (each f=2). This distribution indicates that AR/VR-based educational research is often conducted with small to medium-sized samples. Such studies are generally conducted at the classroom level, and the implementation process is tested on limited groups. Furthermore, the analysis reveals numerous sample sizes with a single frequency. Sample sizes range from 11 to 362; this shows that both small-scale classroom research and experimental studies with larger participation have taken place. The largest sample size is 362, which indicates that some research in the field has the potential for larger-scale applications. Another noteworthy element is the values reported as mixed sample groups (e.g., "21/28" or "99/131"). Such cases sometimes indicate that control and experimental groups were reported separately, or that different groups were used in multi-stage applications. Sample sizes were reported using raw numerical values rather than categorical groupings, as no consistent standards exist in the literature for defining small-, medium-, or large-scale XR studies, and such cut-offs could introduce interpretive bias.

In general, it can be said that there is no homogeneous distribution in terms of sample sizes, but the range of 30–100 participants is the most commonly preferred band. This finding suggests that research is mostly based on practical studies conducted in a single class, a few classes, or at the school level. The number of studies with larger samples is relatively small, which may indicate that generalisability in the field could be limited. Future research needs to both report sample sizes more clearly and to diversify and expand the sample groups.

Significance Frequency Distribution

A significant portion of the articles reported that augmented reality (AR), virtual reality (VR), and mixed reality (MR) applications produced statistically significant effects in educational environments (Table 3).

According to the frequency analysis, in 47 studies, the findings were directly stated as "significant," and the research hypotheses were supported. These significant

Table 3 Frequency Distribution of Significance

Significance	Frequency
Significant	47
Not significant	6
Positive	3
Accurate	1
Balanced	1

Table 4 Frequency Distribution of Technology

Technology	Frequency
VR	31
AR	24
MR	2
VR, AR	1
AR, VR	1

effects were concentrated on key learning outcomes, particularly academic achievement, motivation, student engagement, self-efficacy, and interaction level. However, some studies did not use the term "statistically significant" directly but reported their findings as meaningful in a qualitative context. For instance, in findings classified as "positive" (f=3), the positive effects of AR/VR applications on student motivation and course participation were emphasised; in this respect, the findings produced noteworthy results in a pedagogical sense, even if not statistically so.

Similarly, in a study presented with the expression "balanced" (f=1), the usability of the system (System Usability Scale - SUS) was found to be satisfactory; this, in turn, demonstrates that the technology can be integrated into educational environments in a compatible and functional manner. Again, the term "accurate" (f=1) in a single study pointed to the positive effects of AI-supported systems that could accurately predict neurocognitive data on student engagement, and indirectly offered significant results. On the other hand, in only 6 studies were the findings reported as "not significant". In these studies, methodological limitations such as the short duration of the application, the limited sample size, a low level of interaction with the technological tools, or the lack of sufficient sensitivity in the measurement tools often came to the fore.

When a general evaluation is made, it is seen that in the majority of the reviewed studies, AR/VR/MR-based applications are shown to create statistically or qualitatively significant and positive effects. This situation supports the potential of these technologies to contribute to learning processes; however, it also reveals that the effects are influenced by contextual variables and that well-designed instructional scenarios are of critical importance for the effective use of these technologies.

Technology Frequency Distribution

When the types of technology used in the articles are analysed, it is seen that the majority of the studies were conducted with Virtual Reality (VR) technology (Table 4).

According to the frequency distribution: VR (Virtual Reality) 31, AR (Augmented Reality) 24, MR (Mixed Reality) 2, and studies using both AR & VR: 2 (VR, AR=1; AR, VR=1). These findings show that VR technology has been in a more dominant position in educational applications in recent years. The fully immersive experience offered by virtual reality environments provides significant advantages, especially in representing abstract concepts such as science, mathematics, and engineering in three dimensions. AR (Augmented Reality) technology, ranking second with a high frequency, demonstrates that this technology has practical advantages such as easy integration with mobile devices, ease of in-class application, and low cost. AR applications generally support students' conceptual understanding by presenting learning materials integrated with the real environment. Mixed Reality (MR) technology has so far been used in a limited number of studies (f=2). The reason for this may be that MR applications are still a developing field and have high hardware requirements. Similarly, studies using both VR and AR technologies together are also quite rare (f=2). An increase in such integrated applications could enrich interdisciplinary learning experiences in the future.

When this distribution is evaluated generally, it is seen that VR-based applications are prominent in the technology-focused classification of research, but AR technologies also constitute a strong research area. MR and hybrid applications are still in the developmental stage, and their greater presence in the literature will offer significant opportunities, both theoretically and practically.

Keywords/Index Terms Frequency Distribution (Comma Separated)

Keywords provide important clues about the focus of research and thematic trends. As a result of the frequency analysis of keywords, the most frequently repeated terms include "Virtual Reality" (n=29), "STEM" (n=24), "Augmented Reality" (n=24), "Education" (n=21), and "Mathematics" (n=20). Other terms such as "Science", "Learning", "Motivation", and "Achievement" were used with lower frequency.

Based on these keywords, it is understood that the research is largely focused on the use of VR/AR technologies in STEM education, the enhancement of learning outcomes, and particularly mathematics and science. Furthermore, some studies also addressed the relationship of these technologies with variables such as problem-solving, interaction, cognitive load, and attitude.

The frequency of terms directly referring to technology among the keywords (e.g., immersive learning, 3D, gamification, head-mounted display) also illustrates how the process of digitalisation in the educational environment is being conceptualised. This finding reveals that the conceptual frameworks in the literature are being shaped with a focus on technology. A total of 109 keywords were found. The word cloud for the keywords is shown in Fig. 9.

The frequency analysis conducted on the keywords has provided important data for determining the thematic concentrations and orientations of the research. The results show that the majority of keywords are clustered around technology types, educational areas, learning processes, and pedagogical variables.

1. **Technology Focus (VR/AR/Metaverse)**

   The most prominent keyword in terms of frequency was "Virtual Reality" (n=29). This indicates that virtual reality-based applications are the most preferred technology in STEM education and are extensively studied in the literature. Similarly, the term"Augmented Reality" (n=24) also has a high frequency. Additionally, low-frequency terms such as "Mixed Reality","Extended Reality", "Head Mounted Display","Immersive Learning", "IVR Technology","Virtual Field Trip","Avatars","Self-avatars","2D/3D interaction", "Metaverse", and "Metaverses STEM" demonstrate the diversity of these technologies and that their sub-types are also finding a place in research.

2. **Discipline and Educational Area**

   Among the keywords, concepts such as "STEM" (n=24),"Education" (n=21), "Mathematics" (n=20), and"Science Education" (n=12) were used with high frequency. This distribution reveals that the research is largely shaped in STEM disciplines, especially in the context of mathematics and science education. Furthermore, the presence of terms related to student grade levels such as "K-12", "Middle School","Primary School", "High School" shows that student age groups are also taken into account in the studies.

3. **Learning Processes and Pedagogical Approaches**

   Keywords such as "Motivation/Engagement" (n=8), "Learning Outcome" (n=2), "Cognitive Load" (n=1), "Conceptual Understanding" (n=1), "Representational Fluency" (n=1), "Creativity" (n=1), and "Learning Effectiveness" (n=1), "Problem-solving" (n=1) are included. These terms indicate that the research focuses on the cognitive and affective learning outcomes of students. Furthermore, terms emphasising learning by doing, such as "Active Learning","Collaborative Learning", "Hands-on","Inquiry-based Learning", "Making", "Maker Education", "Maker Self-efficacy", are also noteworthy.

4. **Technology-learning Integration**

   Terms such as "Technology Integration" (n=8), "Usability" (n=2), "User Experience" (n=1), and "Learning Tool" (n=1) indicate a focus on the forms of adoption of digital technologies in learning environments. Additionally, data-driven monitoring and evaluation concepts such as "Artificial Intelligence", "Artificial Intelligence Education","Functional Near Infrared

Fig. 9 Word cloud of keywords

Spectrometry (fNIRS)","Engagement Detection", and "Predictive Model" also signal the integration of technological tracking systems into education.

5. **Contextual and Current Approaches**

Some keywords show that current themes and societal focuses are also addressed in the studies. For example: "Covid-19" (n=2): Research on the role of technology in education during the pandemic."Girls in STEM", "Diversity", "Latinx": Social dimensions such as inclusivity and gender equality. "SDGs" (Sustainable Development Goals), "Ethics", "Participatory Research": Focuses on ethics, participatory processes, and sustainability in education.

In conclusion, the frequency analysis shows that the keywords “Virtual Reality”, “STEM”, “Augmented Reality”, “Education”, and “Mathematics” are particularly prominent. These trends reveal that the main focus of the research is on technology-based education and the pedagogical effects of AR/VR applications in the STEM field. Lower-frequency but meaningful concepts reflect pedagogical sub-headings such as learning outcomes, motivation, interaction, and cognitive load. This multi-layered distribution indicates that AR/VR-supported educational research touches upon not only technology but also fields like learning science, psychology, ethics, and social justice. The diversity of keywords supports the interdisciplinary nature and developmental potential of the literature. The network structure of the keywords is shown in Fig. 10.

Country Frequency Distribution (Comma Separated)

The frequency analysis conducted by country has revealed that the highest number of studies were conducted in the USA ($n=11$) and Taiwan ($n=10$). China ($n=7$), Spain ($n=4$), and Turkey ($n=4$) are other countries that have produced noteworthy studies in this field. This distribution shows that research on virtual and augmented reality technologies and STEM education is concentrated in the USA and the Asian region. The studies conducted in Europe, especially in Spain and Turkey, also establish this field as a widespread international research topic. Although there are fewer studies in other countries, they demonstrate the interest and potential of various countries on a global scale. On the other hand, the absence of any study from the continents of Africa and South America can be considered a significant gap. The countries where at least two studies were conducted are listed in Table 5.

Bibliography Frequency Distribution

Bibliographic analysis has provided important findings for evaluating researcher density, collaboration patterns, and academic productivity in the field. The vast majority of the articles included in the research have a multi-author structure. This situation shows that the field is shaped by a production model based on collaboration. Authors with more than one article are shown in Table 6.

Among the most prolific authors are names such as Makransky, Mayer, Xie, Rossano, Cai, Liu, and Chen. These researchers focus on both AR/VR technologies and

Fig. 10 Relational network structure of keywords

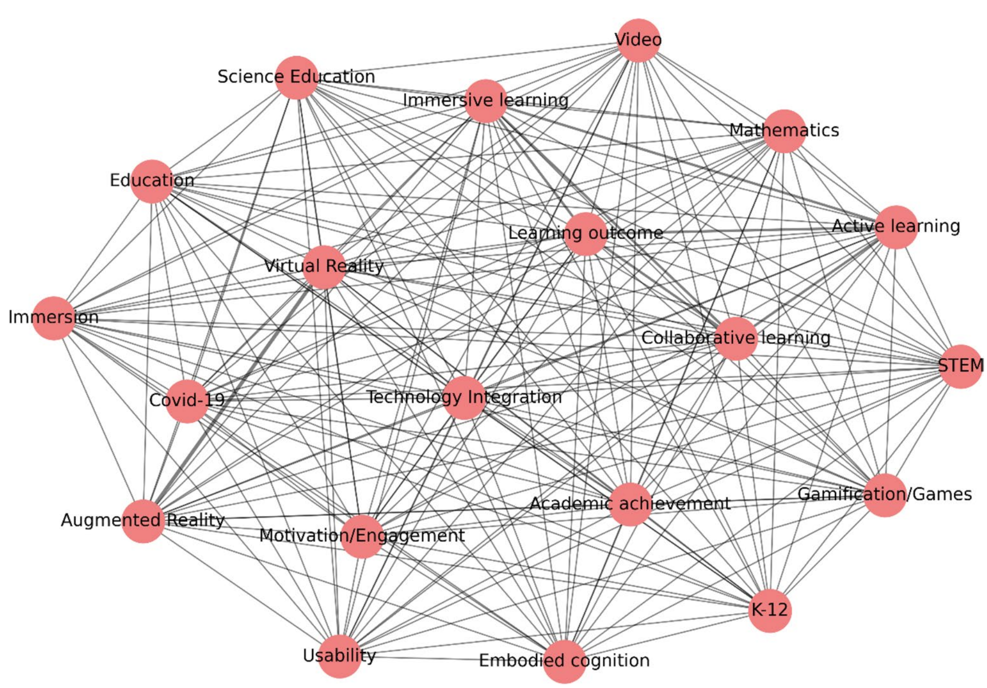


Table 5 Country Frequency Distribution

Country	Frequency
USA	11
Taiwan	10
China	7
Spain	4
Turkey	4
Malaysia	3
Denmark	3
Australia	2
Cyprus	2
Greece	2
UK	2
Indonesia	2
Mexico	2
Pakistan	2
Italy	2

Table 6 Bibliography Frequency Distribution

Bibliography	Frequency
Makransky, G.	3
Klingenberg, S.	2
Xie, Y.	2
Rossano, V.	2
Mayer, R.E.	2
Liu, R.	2
Cai, S.	2
Petersen, G.B.	2
Wang, L.	2

multimedia learning theories, contributing to topics such as learning outcomes, engagement levels, motivation, and self-regulation. When evaluated in terms of citation counts, the most cited study belongs to Sahin and Yılmaz (2020), with 387 citations. This study comprehensively evaluated the effects of AR technology on middle school students. It is followed by VR studies conducted as a multi-author collaboration by Makransky and Mayer. Author collaboration network analyses show that some authors work together repeatedly on different projects. For example, pairs like Makransky & Petersen or Rossano & Rebollo have conducted joint research on more than one study. Such collaborations reflect the continuity and consistency of academic focal points of specialised research teams in the field. The author collaborations are shown in Fig. 11.

The network analysis shows that the authors who have published frequently together are divided into five main clusters:

- **Makransky - Petersen - Mayer - Klingenberg cluster**: These authors have generally produced VR-focused studies in high-impact journals such as the *British Journal of Educational Technology* and *Educational Psychology Review*. Makransky stands out with his studies examining the effects of VR on motivation, presence, and learning outcomes. His collaborations with Petersen and Mayer have developed particularly within the framework of multimedia learning theories.
- **Cai – Shen - Jiao – Li – Liu – Liang – Yang cluster**: This group is prominent in studies based in China and Taiwan, examining the effects of AR/VR applications on students' self-efficacy, academic achievement, and conceptual understanding in the STEM field. The existence of numerous co-authored publications shows that this group has formed a coordinated and stable collaboration network.
- **Rossano - Lanzilotti – Roselli – Cazzolla – Rebollo - Remolar cluster**: This cluster includes studies designing augmented reality-supported learning environments, especially in the context of geometry and mathematics education. A notable feature of this group is its European-centric nature (especially Spain and Italy). The duo of Rossano and Rebollo are marked by multiple connections on the network.
- **Wang - Liu - Ren – Lei – Koszalka – Wan cluster**: This group, led by Wang Q. and Liu R., has experimentally investigated AR/VR-supported virtual classroom applications and their effects on students' cognitive load, motivation, and academic performance. The high connection density of this group in the visual indicates tight academic collaborations.
- **Xie – Zhang and other scattered authors**: Apart from the small cluster formed by Xie and Zhang, there are also several independent or weakly connected authors in the visual. These authors have mostly taken part in single studies or have not assumed a bridging role between research groups.

The size of the nodes on the network is proportional to the authors' publication count, while the thickness of the edges is proportional to the frequency of co-publication. This visual analysis shows that authors like Makransky, Wang, Cai, and Rossano are prominent both in terms of publication count and centrality in the collaboration network. In terms of citation count, the study by Sahin and Yılmaz (2020) is at the top of the list with 387 citations; however, as this study is not located directly at the centre of the network in the visual, it points to a more independent production. On the other hand, it is clearly observed in the visual that high-publication authors like Mayer and Makransky produce continuously in collaboration. In conclusion, this author network structure shows that publications in the field are produced not only individually but also through interdisciplinary and multi-author partnerships, and for this reason, a collaboration-based research culture has become firmly established.0

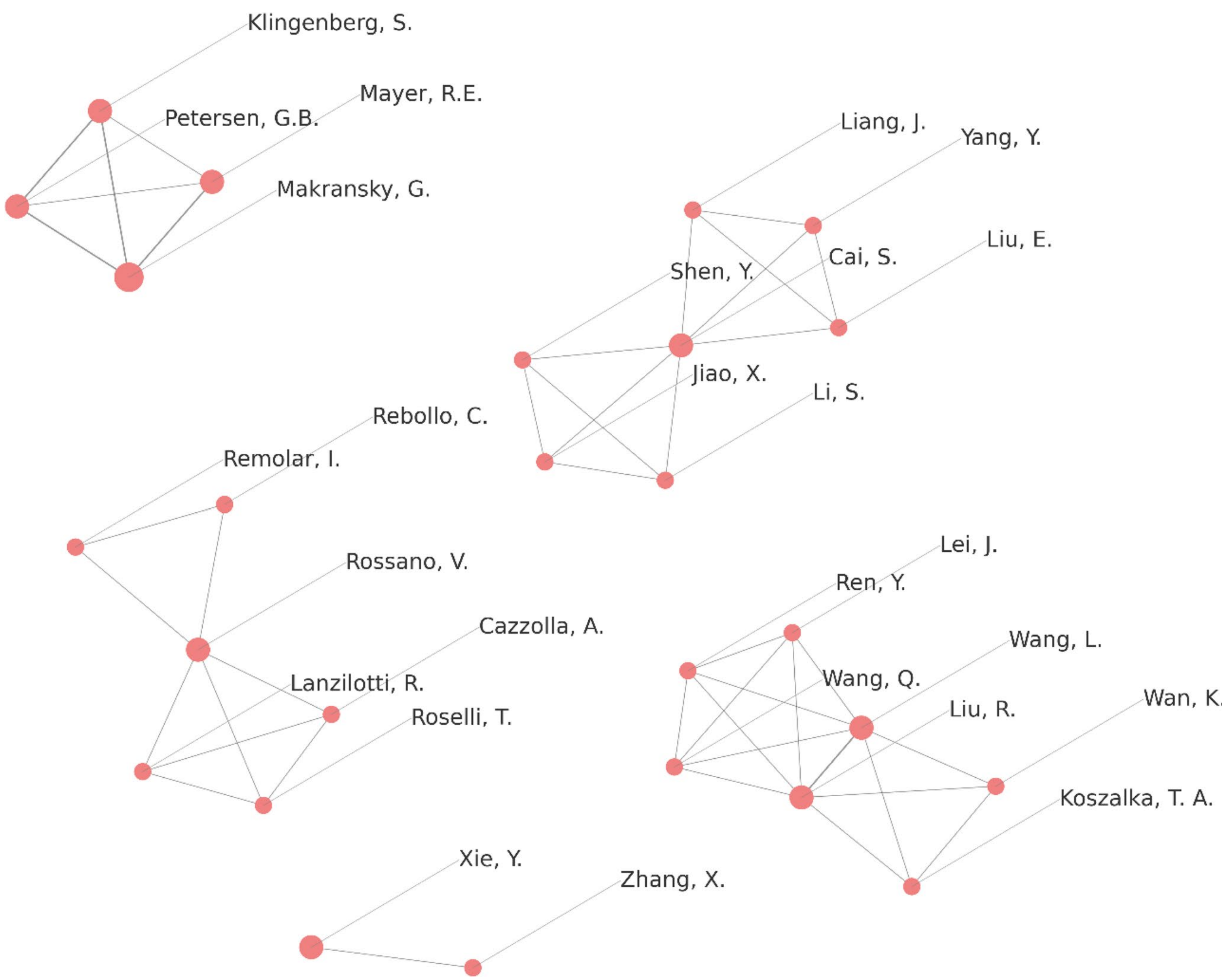


Fig. 11 Author collaboration network structure

Discussion

The findings of this study corroborate the growing body of evidence regarding the effects of technologies such as augmented reality (AR), virtual reality (VR), mixed reality (MR), and extended reality (XR) on K-12 STEM education. The content analysis performed reveals not only the pedagogical contributions of these technologies but also their methodological challenges. Within this context, the findings present significant implications for both academic achievement and pedagogical processes.

In terms of student achievement and cognitive gains, numerous studies have demonstrated that AR and VR technologies enhance academic success, particularly in the fields of science and mathematics. For example, a meta-analysis conducted by Flavin et al. (2025) showed that AR has a medium-level significant effect on mathematics achievement. Similarly, Wang et al. (2025) highlighted that an AR-supported mathematics curriculum particularly improves spatial skills in female students. In the context of chemistry education, an MR-based laboratory safety system developed by Chen et al. (2024) increased not only student achievement but also their level of conceptual awareness. Furthermore, Ateş and Polat (2025) stated that when AR-based gamification is combined with self-regulation strategies, it significantly improves both academic achievement and learning satisfaction.

When evaluated in terms of affective outcomes, interest, and attitude, many studies have revealed that technology integration increases students' learning motivation. Hunt et al. (2025) reported the effects of gamified VR applications on both fraction knowledge acquisition and increased interest in STEM. Similarly, Khattib and Alt (2024) indicated that digital gamification applications had a positive effect on student interest and intrinsic motivation. However, Na and Sung (2025) emphasised that AR-supported learning was more effective at the cognitive level than on attitude, while Mulders et al. (2025) noted that while VR could support positive attitudes in environmental education, this change was limited.

From the perspective of learning strategies and pedagogical design, Jiang et al. (2025) stated that AR/VR-supported instructional designs are predominantly based on game-based, task-based, or situational learning; in contrast, they identified various challenges related to teacher control, classroom management, and technical proficiency. These findings align with a systematic review by Stracke et al. (2025), which showed that many XR studies are not yet based on sufficient theoretical foundations or adequately structured. Additionally, Lawson et al. (2024) noted that in media comparison studies, the failure to create equivalent content and methods for experimental and control groups could limit the validity of the findings.

From the perspective of access, equity, and sustainability, Newton et al. (2024) stated that XR technologies offer an opportunity for equity, particularly for students who lack access to place-based learning. They also emphasised that by enabling content with environmental sensitivity to reach a wider audience, these technologies contribute inclusivity and sustainability to learning processes. XR applications remove physical space limitations, providing safe, repeatable, and sustainable learning experiences.

When technology types are compared, it is observed that AR, VR, and MR technologies support different learning outcomes. AR stands out for its concretisation and visualisation capabilities, while VR supports experiential learning and empathy development. MR, in turn, offers unique contributions by providing safe simulations, particularly in experimental science education. In this context, Schmidt and Stumpe (2025) noted that mobile AR applications could be used effectively in geography education but drew attention to shortcomings in the pedagogical framework. On the other hand, the REC-STEMED project conducted by Vasconcelos et al. (2025) demonstrated how robotics and computational thinking can be promoted in early childhood education through teacher training, thereby showing that XR technologies present significant opportunities not only for student outcomes but also for teacher competencies.

When the conducted studies are examined, it is generally observed that they focus on small- and medium-scale samples. Thomann et al. (2024), while evaluating the learning outcomes of VR technologies in vocational education, stated that the generalisability of the results was low due to the limited sample size. In their meta-analysis on the effects of educational robotics, Ouyang and Xu (2024) also emphasised that studies conducted with larger samples yield more consistent results.

Cultural and contextual factors also play a significant role in the effectiveness of XR technologies. Schott et al. (2024) noted that cultural and pedagogical differences in VR applications in New Zealand led to implementation challenges. Similarly, Mulders, Träg, and Kirner (2024) suggested that VR applications in environmental sustainability education in Germany should be examined in more detail across different cultural contexts. Chin et al. (2024) also stated that museum-based mobile MR learning systems in Taiwan require further research in terms of cultural context sensitivity.

A large portion of the studies utilising XR technologies have been published in high-impact-factor, Q1-category journals, which increases the academic validity of the findings. Chen et al. (2025) emphasised that studies on integrated STEM education published in Q1-category journals possess a higher scientific quality. Lawson et al. (2024) also supported this view, drawing attention to the importance of methodologically consistent investigation of VR applications.

Zhang et al. (2024) have suggested that the literature could be explored in greater depth through an umbrella review of the use of AR and VR technologies in STEM education.

In conclusion, while AR, VR, MR, and XR technologies offer positive effects across many dimensions, from student achievement to attitude and from access to pedagogical design, it is of great importance that these effects are structured in a sustainable, accessible, and theoretically grounded manner. Hunt et al. (2025) drew attention to the issue of scalability to ensure that game-based interventions can be applied to wider audiences. Chen and Huang (2024) stated that research is needed on how collaborative learning in Metaverse environments can be made more effective for programming education. Damaševičius and Sidekerskienė (2024) emphasised the potential of virtual worlds to develop critical thinking, creativity, and collaboration skills in students, highlighting the need for more in-depth research in this area.

Conclusions and Suggestions

This study has presented a multidimensional systematic content analysis of the effects of augmented reality (AR), virtual reality (VR), mixed reality (MR), and extended reality (XR)technologies on K-12 STEM education. The findings, obtained from the review of 59 academic articles published between January 2019 and June 2024, demonstrate that these technologies offer significant and positive effects, particularly on academic achievement, learning motivation, cognitive gains, attitudes, and learning strategies.

According to the research findings, it is observed that VR and AR-based applications increase students' achievement levels, develop their scientific process skills, and support intrinsic motivation for the learning process. However, it is also noted that XR technologies present certain pedagogical challenges in areas such as instructional design, classroom management, and technical proficiency. Furthermore, it is understood that factors such as cultural context, sample size, and technology type play a decisive role in the effectiveness of these technologies.

The majority of the articles analysed within the scope of the study were structured based on experimental and quantitative methods, with research focusing particularly on middle school students and employing active learning strategies such as gamification and task-based learning. However, it is understood that there is a need for increased theoretical grounding and methodological diversity in the integration of XR technologies into learning environments.

In line with these findings, the following recommendations have been developed:

i. Sample Breadth and Representativeness: Future studies should be conducted with larger and more diverse sample groups to increase the generalisability of the results. There is a need for comparative research across different age groups, socioeconomic levels, and cultural contexts.
ii. Increased Use of Qualitative and Mixed Methods: To understand students' experiences with XR technologies more deeply, qualitative and mixed methods should be used more extensively. This will allow for the interpretation of not only the learning outcomes but also the learning process itself.
iii. Theoretical Grounding and Design-Based Research: The use of robust pedagogical theories and learning models in the design of XR-supported learning environments will increase the quality and effectiveness of the applications. In this context, approaches such as learning-by-doing, situated learning, and constructivism can be guiding.
iv. Principles of Access and Inclusivity: For XR solutions developed for student groups with limited access to technology, the design of low-cost, easily accessible, and inclusive applications is of great importance. In this context, mobile learning applications and open-source solutions should be prioritised.
v. Teacher Education and Digital Competency: It is necessary to enhance the digital pedagogical competencies of teachers through professional development programmes so that they can effectively integrate XR technologies into the classroom environment. These programmes should be practical, sustainable, and interdisciplinary.
vi. Focus on High-Impact and Innovative Publications: Considering that the majority of the research published in the field appears in Q1 and Q2 level journals, future studies should also maintain this level of academic quality, while it is also recommended to integrate XR technologies with innovative themes such as artificial intelligence, learning analytics, and personalisation.
vii. Policy Development and Practitioner Guidance: It is essential that policymakers and school administrators who determine education policies recognise the pedagogical potential of XR technologies and provide the necessary infrastructure, instructional materials, and teacher support for these technologies.

In conclusion, while XR technologies possess high potential in the context of K-12 STEM education, multidimensional developments are needed in areas such as instructional design, teacher education, accessibility, and research methodology to realise this potential effectively. In this context, interdisciplinary and innovative research will reveal the effects of XR technologies on learning environments in greater depth.

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Data Availability All data supporting the findings of this study are included within the article. The complete dataset is available from the corresponding author upon reasonable request.

Declarations

Ethical Approval Not applicable. This study is a systematic content analysis of previously published academic articles and did not involve direct research with human participants or animals.

Informed Consent Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

Competing Interests The authors declare that they have no competing interests.

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