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PAPER

Virtual, Augmented, and Mixed Reality in STEM Education in Asia: A Bibliometric Review (2015–2026)

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ABSTRACT

The use of virtual, augmented, and mixed reality (VAMR) technologies in various domains has increased over recent years. However, reviews of their application in science, technology, engineering, and mathematics (STEM) education, particularly in Asia, remain limited. This study presents a bibliometric review of VAMR research in STEM education in Asia from 2015 to 2026 to map research trends, intellectual structures, and knowledge development in this field. A total of 122 publications were retrieved from the Scopus database. RStudio Bibliometrix and VOSviewer were employed to perform a bibliometric analysis. The findings indicate a steady growth of VAMR research in STEM education among Asian countries over the past decade. Taiwan, China, and Turkey emerged as the most influential countries in terms of citation output. Nanyang Technological University and Universiti Kebangsaan Malaysia were identified as the most productive institutions with 7 publications each. *Electronics (Switzerland)* was the most influential journal in the field with 266 citations. The most influential article, authored by AlGerafi et al., received 237 citations. Keyword co-occurrence analysis highlighted "augmented reality," "STEM education," "STEM," "virtual reality," and "systematic review" as dominant themes, reflecting the central focus of current research. This study offers a comprehensive overview of VAMR research in the context of STEM education in Asia and provides a basis for identifying emerging trends and future research directions.

KEYWORDS

virtual reality (VR), augmented reality (AR), mixed reality (MR), science, technology, engineering, and mathematics (STEM) education, Asia, bibliometric analysis, SCOPUS

1 INTRODUCTION

Nowadays, the rapid advancement of digital technologies has significantly changed how education is delivered, particularly in science, technology, engineering, and mathematics (STEM) education. It is believed that STEM education emphasizes interdisciplinary problem solving, fostering technological literacy, creative thinking, and critical thinking [1]–[3]. Previous research indicates that STEM approaches

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promote cross-disciplinary learning [4] and yield significant improvements in student STEM career interests and achievement [5]. Beyond educational context, STEM education has also been associated with broader socioeconomic benefits, including employment opportunities, increased labor productivity, and economic growth [6], [7]. Nonetheless, STEM disciplines are often perceived as complex, abstract, and multidimensional, requiring learners to interpret multiple representations that may appear disconnected from their daily lived experiences [8], [9]. On the other hand, traditional instructional approaches frequently struggle to increase engagement and provide authentic inquiry opportunities under constraints of time and infrastructure [10]. In response, immersive digital technologies, such as augmented reality (AR), virtual reality (VR), and mixed reality (MR), have emerged as promising tools capable of enhancing visualization and experiential learning [11]–[16].

Despite the growing body of existing research demonstrating the pedagogical affordances of VR, AR, and MR in STEM education (VAMR-STEMEd), significant gaps remain. First, existing research is predominantly situated in Western countries [14], [17]–[19]. As a result, there is a limited systematic understanding of how immersive technologies are evolving within Asia. This gap is significant given the region's rapid digital expansion, strong patent production, and growing technological leadership [20], [21]. In addition, Asia hosts approximately 60% of the global population and has implemented extensive educational reforms to enhance innovation and competitiveness [22]. However, no comprehensive bibliometric mapping has synthesized the intellectual structure, collaboration networks, and thematic trajectories of VAMR-STEMEd across Asian countries. While constructivist and experiential learning perspectives suggest that immersive technologies should align with STEM education [23], the growth trends of publications, collaboration intensity, and thematic evolution in Asia remain unclear.

Previous studies have examined the development of VAMR in educational contexts; however, their scopes remain limited in terms of geography, educational level, and disciplinary focus. For instance, Maas and Hughes [24] reviewed literature on VR, AR, and MR in K-12 settings published between 2006 and 2017. They provided an early synthesis of immersive technologies in school education. Guo et al. [18] conducted a bibliometric analysis of extended reality research in education from 1991 to 2021. They offered a global overview without specific emphasis on STEM or regional distribution. More recent studies [17], [19] analyzed publications on immersive technologies from the Scopus database. However, their focus centered on teaching-learning processes and university environments rather than STEM education as a distinct domain. Similarly, Çavdara and Yıldırım [25] combined systematic review and bibliometric mapping to explore MR, AR, and VR in STEM education (2013–2022). Nevertheless, their scope was not geographically delimited and was limited to publications up to 2022. These studies demonstrate the growing attention of scholars worldwide to immersive technologies. Nevertheless, they reveal several limitations, including the lack of a focused regional analysis in Asia, limited coverage of the most recent publication years, and insufficient integration of VR, AR, and MR trends specifically within STEM education. Therefore, it is crucial to address this gap to generate valuable insights into whether the digital momentum of Asian countries is reflected in VAMR-STEMEd research.

1.1 Purpose and research questions

This study aims to conduct a bibliometric review of VAMR-STEMEd in Asia. The study is guided by the following research questions: (i) What are the publication and citation trends of VAMR-STEMEd in Asia? (ii) Which countries, institutions, and authors are leading in this field? (iii) Which journals and publications are most cited? and (iv) What are the current trending topics and key insights shaping VAMR-STEMEd research in Asia? By providing a systematic intellectual mapping of this domain, the study informs researchers, educators, and policymakers on the trajectory, strengths, and future directions of immersive technology integration in STEM education in Asia.

2 LITERATURE REVIEW

2.1 VR

Virtual reality is generally defined as an interactive, multisensory environment that allows users to experience a sense of presence in a computer-generated three-dimensional environment [13], [26]. By integrating visual, auditory, and haptic feedback, VR allows learners to interact with virtual objects and environments as though physically situated within them [18], [27]. VR serves as a pedagogical tool that supports constructivist and learner-centered approaches by enabling students to explore abstract concepts, manipulate complex systems, and test hypotheses in realistic yet controlled simulations [13], [28], [29]. Its capacity to create authentic and safe learning environments, particularly for scenarios that are hazardous, costly, or otherwise inaccessible, further enhances the instructional value of VR [30], [31]. Previous literature demonstrates that VR can improve learning achievement and enjoyment [32]–[35], largely due to heightened presence and engagement [29], [32], [36].

2.2 AR

Augmented reality is a technology that enriches the physical world by superimposing digital elements, such as text, graphics, audio, and 3D virtual objects, onto real-time views of the surrounding environment, thereby integrating virtual information with authentic contexts [24], [37], [38]. Unlike VR, which replaces the real environment with a fully simulated one, AR blends computer-generated content with the user's immediate setting to create a seamless interaction between physical and digital spaces [17], [39]. AR holds significant pedagogical potential because it enables learners to visualize abstract, microscopic, or inaccessible phenomena, thus supporting deeper conceptual understanding [40]–[42]. Previous studies report that AR integration contributes to improved achievement, promoted motivation, fostered participation, enhanced engagement, and reduced cognitive load [39], [43]–[47]. Its interactive features align with constructivist learning principles, as learners actively engage with authentic problems and construct knowledge through meaningful experiences [12].

2.3 MR

Mixed reality refers to a technology positioned along the reality-virtuality continuum proposed by Milgram and Kishino [48], in which physical and virtual elements coexist and interact dynamically within a shared environment [19], [24]. Distinct from VR, which fully immerses users in computer-generated spaces [13], and AR, which superimposes digital content onto the physical world [17], MR enables shared and spatially grounded interaction between real and digital objects through advanced sensing systems and head-mounted displays [18], [49]. This integration fosters immersive and embodied experiences that enhance users' sense of presence and engagement [11], [31]. MR demonstrates considerable pedagogical potential by supporting the visualization and manipulation of abstract and complex phenomena, thereby facilitating deeper conceptual understanding [31], [50]. Earlier studies also indicate that the use of MR applications is associated with higher motivation and greater learning outcomes compared to traditional teaching methods [11], [31].

2.4 STEM Education

STEM education refers to an interdisciplinary educational approach that integrates STEM into a coherent learning framework designed to equip learners with essential twenty-first-century skills [1], [8], [51]. It plays a crucial role in preparing students for participation in a technology-driven society and in addressing global challenges [2], [4], [5]. Consequently, many countries position STEM education as a national priority to strengthen workforce readiness and foster innovation in STEM industries [6], [9]. Numerous studies suggest that STEM education promotes learning outcomes across educational levels (i.e., from K-12 to higher education) [8]. However, STEM disciplines are inherently complex, multidimensional, and often abstract, which can make them difficult for students to comprehend. These characteristics also pose challenges for effective integration into traditional curricula that are constrained by limited time and resources [52]. Moreover, declining student motivation toward STEM subjects as grade level increases [53], [54] further complicates implementation efforts. In this context, immersive digital technologies such as VR, AR, and MR offer promising solutions that make abstract concepts more tangible and support experiential learning, thereby strengthening students' interest, engagement, and achievement in STEM education [23], [28], [33], [47].

3 METHODOLOGY

3.1 Bibliometric approach

This study adopted a bibliometric approach to examine publication patterns, intellectual structures, and emerging trends related to VAMR-STEMEd across Asia. Bibliometric analysis allows researchers to evaluate the scientific literature by mapping research developments, scientific impact, and thematic evolution within a particular field [55]. In recent years, this approach has been increasingly employed by researchers worldwide to assess knowledge production, identify influential contributions, and detect emerging research trajectories across various disciplines [17], [37]. Accordingly, this study applied bibliometric techniques to analyze the growth, citation impact, collaboration patterns, and thematic trends of VAMR research in STEM education within the Asian context.

3.2 Search strategy

The bibliometric mapping analysis was conducted using data retrieved from the Scopus database. Scopus was selected because of its broad coverage of peer-reviewed publications and rigorous indexing standards, which ensure the inclusion of high-quality and reliable sources [56]. Data collection was performed through the Scopus search engine, a widely recognized and reputable academic database commonly used in bibliometric studies. To enhance the comprehensiveness of the search results, a symbol (*) was incorporated into the search query to capture variations of relevant terms. For example, the use of "STEM educat*" allowed retrieval of documents containing both "STEM education" and "STEM educators." On February 6, 2026, a systematic search was conducted across the title, abstract, and keyword fields using the query outlined in Table 1. This initial search yielded 979 records related to VAMR and STEM education.

Table 1. The search string

Topic	Search String
VR/AR/MR	"augmented reality" OR "augmenting reality" OR "virtual reality" OR "virtual immersive reality" OR "immersive reality" OR "virtual environment" OR "virtual world" OR "mixed reality" OR "extended reality"
AND STEM Education	"STEM learn*" OR "STEM educat*" OR "STEM teach*" OR "STEM lesson*" OR "STEM major*" OR "STEM activit*" OR "STEM field*" OR "STEM classroom*" OR "STEM course*" OR "STEM discipline*" OR "STEM context*" OR "STEM student*" OR "STEM approach*" OR "Science, Technology, Engineering, Math*" OR "Science, Technology, Engineering, and Math*" OR "Science, Technology, Engineering and Math*"

To ensure methodological transparency and rigor, the study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [57]. This framework guided the research process through four sequential stages: identification, screening, eligibility, and inclusion of relevant studies. The detailed selection process and the number of records retained or excluded at each stage are illustrated in Figure 1.

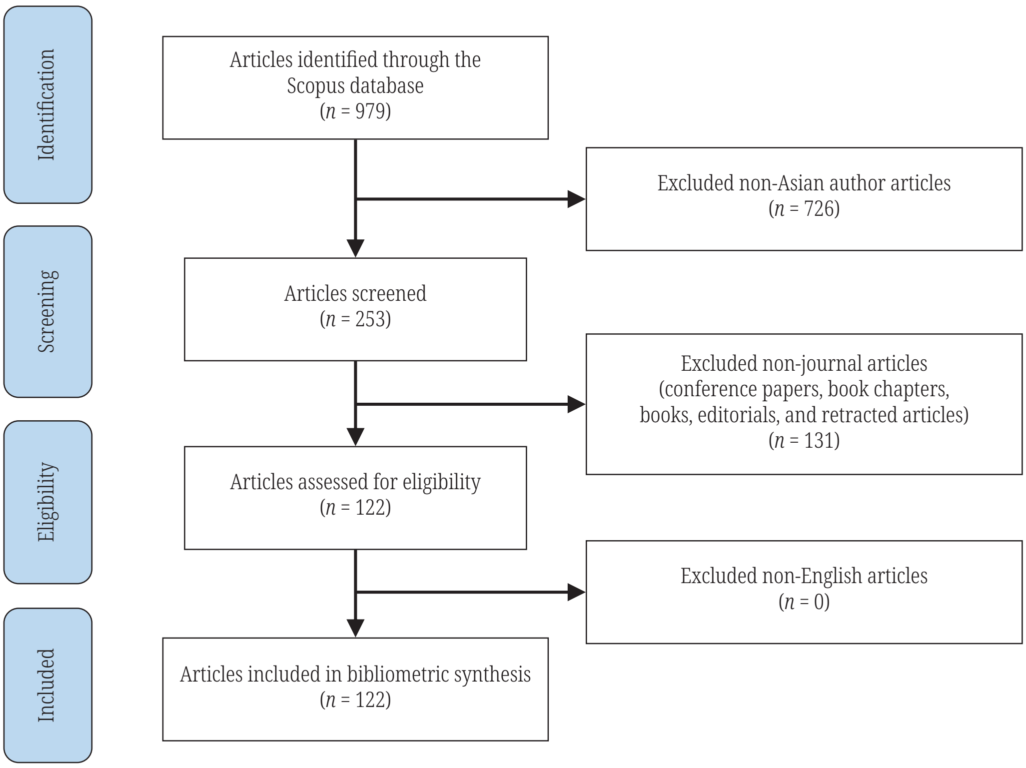


Fig. 1. Article selection process

3.3 Inclusion and exclusion criteria

Following the initial retrieval, a screening process was applied to refine the dataset based on predefined inclusion and exclusion criteria (see Table 2). No restrictions were applied regarding publication year and language. The time frame of the study was set from January 2015 to February 2026. This year was chosen because it marked the earliest publication on VAMR-STEMEd in Asia within Scopus. Only peer-reviewed journal articles were considered, while other document types, including conference papers, book chapters, books, editorials, and retracted publications, were excluded to maintain academic rigor and consistency. Additionally, only articles authored by researchers affiliated with institutions in Asia were included. This aimed to ensure that the present study accurately reflected the regional research landscape. After applying these criteria, the dataset was reduced from 979 to 122 eligible records. It is worth noting that all documents were in English; there were no non-English-language articles in the dataset. All selected articles were subsequently downloaded and stored in CSV format for further analysis. It should be noted that the exclusion of non-Asian authors and non-journal publications was implemented to ensure methodological consistency and data comparability.

Table 2. Inclusion and exclusion criteria

Criteria	Inclusion	Exclusion
Year of publication	Publications from Jan 2015 to Feb 2026	Other than the specified range
Type of publication	Articles and reviews	Books, book chapters, conference papers, editorials, retracted papers
Type of source	Journals	Book series, books, conference proceedings, etc.

3.4 Data analysis

This study integrates both quantitative and qualitative bibliometric techniques to provide a comprehensive assessment of VAMR-STEMEd research in Asia [55]. Performance analysis was conducted to evaluate the scientific contributions of institutions, countries, authors, and journals. This enabled the identification of the most productive and influential contributors within the field. To explore the intellectual structure and collaboration patterns of the research domain, science mapping techniques were employed, particularly co-authorship and keyword co-occurrence analyses. Co-authorship analysis was used to examine collaboration networks among authors and countries. Meanwhile, keyword co-occurrence analysis was utilized to identify dominant themes, conceptual relationships, and emerging research clusters within the literature.

For visualization and network mapping, the study employed two widely recognized bibliometric tools: Bibliometrix [58] and VOSviewer [59]. The Bibliometrix R package (version 4.4.1) was employed to conduct the bibliometric analysis. VOSviewer (version 1.6.20) was used to generate co-authorship networks, keyword co-occurrence maps, and thematic clusters. In these visualizations, each node represents a keyword, while the connecting lines indicate relationships based on their co-occurrence within the same publications. The size of nodes and link thickness reflect the frequency and strength of associations among keywords. Additionally, Microsoft Excel was utilized for preliminary data extraction and cleaning prior to further bibliometric processing and visualization.

4 RESULTS AND DISCUSSION

4.1 General information

Table 3 summarizes the main information from documents published between 2015 and 2026. The earliest publication in the dataset appeared in 2015, when Wang et al. [60] introduced a model-based inquiry–virtual physics lab pedagogical framework designed to enhance scientific inquiry in physics learning. Since then, the field has experienced steady growth. The dataset comprises 122 documents published across 87 journals. This reflects the diverse publication landscape and increasing scholarly attention to the field. The annual growth rate of 13.43% indicates a trending interest in VAMR research, in line with advances in digital technology and the increasing adoption of immersive technologies in education worldwide. Within the dataset, the average age of documents is 2.87 years, indicating that most contributions are novel. With an average of 18.32 citations per paper, this field exhibits a moderate level of scientific impact and visibility. It can be said that VAMR studies in STEM education are well-referenced within the academic community. When analyzed, authorship patterns reveal a collaborative research culture, as evidenced by an average of 3.80 co-authors per document and a pool of 431 contributing authors. Interestingly, only six of the papers were written by a single author. This reinforces the notion that this field is inherently interdisciplinary, requiring the integration of expertise in education, immersive technologies, and specific STEM domains. Additionally, the identification of 387 author keywords highlights thematic diversity within the dataset. Moreover, the proportion of international co-authorships, amounting to 29.51%, indicates a relatively modest level of cross-national collaboration in this area. This pattern suggests that the field, while growing, remains regionally concentrated and insufficiently integrated into a broader global research network. The limited proportion of international partnerships may be explained by the complexity of VAMR-STEMEd studies, which often require adequate technological infrastructure, interdisciplinary expertise, and financial investment. Moreover, disparities in technological access and research capacity across Asian countries appear to constrain collaborative opportunities. As reported by Nipo et al. [61], technological inequalities remain a significant concern in the Asian region.

Table 3. Main information about the extracted data

Description	Results	Description	Results
Timespan	2015–2026	Authors	431
Sources	87	Author's keywords	387
Documents	122	Authors of single-authored docs	6
Annual growth rate %	13.43	Single-authored docs	6
Document average age	2.87	Co-authors per doc	3.80
Average citations per doc	18.32	International co-authorships %	29.51

4.2 Annual scientific productions

Figure 2 demonstrates a substantial upward trajectory, particularly from 2019 onward. The period between 2015 and 2018 shows relatively limited output, with only one to three articles per year. This suggests that VAMR-STEMEd was still an emerging research area in Asia during this phase. From 2019 to 2021, there was a gradual increase in publications, indicating growing academic interest and early consolidation of the field. A more pronounced acceleration occurs after 2022, especially in 2024 and 2025, where the number of publications rises sharply to 28 and 40 articles, respectively. This surge reflects the rapid expansion of VAMR research, likely driven by technological advancements, increased accessibility of immersive technologies, and heightened recognition of their pedagogical potential in STEM learning. The high coefficient of determination ($R^2 = 0.94$) for the period from 2015 to 2025 confirms that the growth in publications follows a predictable upward trend, indicating strong momentum in the field. Although the number of publications in 2026 appears lower (four articles), this figure likely reflects partial-year data, as the data were obtained in early February 2026. Given the previous growth pattern, it is reasonable to conclude that the number of publications in 2026 is expected to continue to increase and likely surpass previous years.

This upward trajectory is consistent with global publication trends on VAMR in education [18], [19], [49]. This trend can be explained by rapid technological advancements alongside the pedagogical alignment between immersive technologies and the complexity of STEM disciplines, which are often abstract, multidimensional, and difficult to visualize [2], [6]. By enabling learners to engage with simulated laboratories, manipulate 3D representations, and visualize inaccessible phenomena, VAMR helps address instructional challenges in STEM education [12], [13], [40]. At the same time, the growing global emphasis on STEM as a driver of innovation, workforce development, and economic competitiveness [1], [2], [7] has increased the urgency to modernize pedagogical practices, thereby strengthening scholarly attention to VAMR in STEM education.

Furthermore, the increasing volume of publications in this field can be attributed to increasing smartphone ownership and decreasing hardware and software costs. The ubiquity of mobile devices has made AR and VR applications readily accessible through smartphones and tablets [62]. The decreasing price of mobile devices has enabled broader integration of 3D content and interactive learning experiences. The advent of low-cost VR headsets like Google Cardboard and Gear VR, compared to more expensive desktop systems like the Oculus Rift, has further reduced institutional barriers and supported the BYOD (Bring Your Own Device) approach [63]. The policy shift toward mobile learning and BYOD practices, along with the need for flexible distance learning during the COVID-19 pandemic [64], [65], has accelerated the use of mobile VAMR technologies to provide self-paced and immersive learning experiences for students.

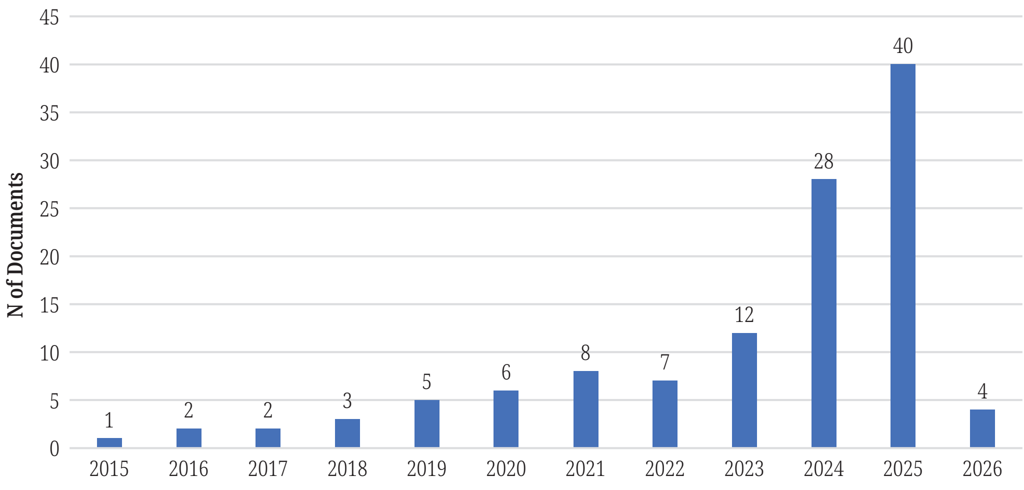


Fig. 2. Number of documents published annually (2015 to 2026)

Regarding the annual pattern of mean total citations (TC) per document (see Figure 3), a fluctuating trend is observed. This reflects the maturity of the VAMR-STEMEd research field and the time-dependent nature of citation accumulation. In the early period, 2015 exhibits a notably high mean citation value. It can be argued that a small number of highly influential pioneering studies attracted substantial scholarly attention as VAMR technologies began to gain traction in STEM education. This is followed by a sharp decline in 2016, implying either a growth in publication volume with fewer highly cited works or a transitional phase in the field. From 2017 to 2018, the number of citations increased again, indicating the emergence of more highly cited studies. The period from 2020 to 2022 reflects a relative stabilization, with a particularly strong peak in 2022. This trend is likely related to the increased interest in research related to the use of digital technologies during and after the COVID-19 pandemic. However, 2023 marks a decline from this peak, suggesting that while research output may continue to grow, the influence of articles is beginning to spread across the literature. From 2024 onward, there is a pronounced downward trend in mean total citations, with 2024, 2025, and 2026 displaying very low values. This pattern should not be interpreted as a decline in research quality but rather as a natural consequence of citation latency, as newer publications have had limited time to accumulate citations [66].

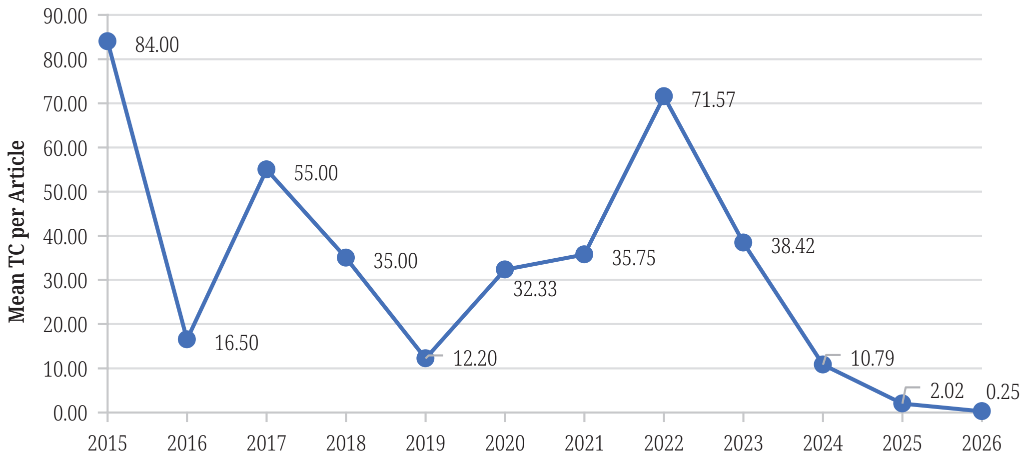


Fig. 3. Average citations per document (2015 to 2026)

4.3 Most prolific countries

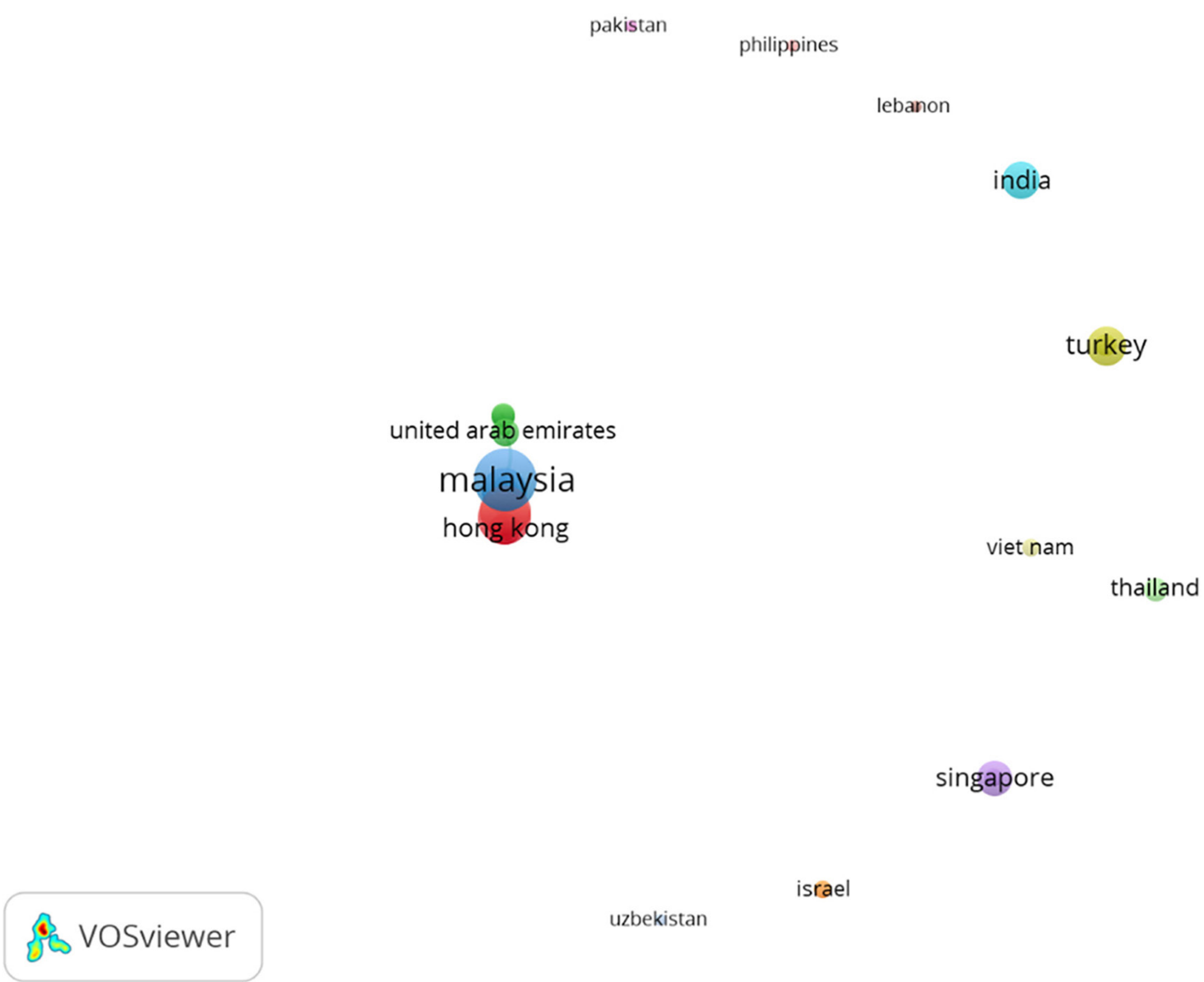
Table 4 lists a ranking of the top 10 most impactful countries/regions in research on VAMR-STEMEd in Asia. Taiwan, China, and Turkey emerge as particularly influential, albeit through different patterns of performance. Taiwan demonstrates a strong balance between productivity and impact, with a high total citation count (TC = 542) derived from a relatively moderate number of publications (TP = 17), resulting in a substantial average citation per publication (ACP = 31.88), which suggests that its contributions are widely recognized in the field. China, while producing the largest number of publications among the top three (TP = 18), exhibits slightly lower scholarly impact per publication (ACP = 28.61), indicating a strategy characterized by higher research volume with somewhat more dispersed citation influence, yet still maintaining a very high visibility (TC = 515). Singapore, in contrast, despite a smaller publication output (TP = 8), achieves the highest ACP (37.88) among the leading countries, reflecting a strong emphasis on high-impact studies that shape academic discourse in immersive technologies for STEM education. In terms of average number of citations per document, Turkey and the United Arab Emirates display relatively high ACP values (32.30 and 33.80, respectively) despite limited publication counts. This suggests that their contributions, while fewer, tend to attract considerable scholarly attention.

It is noteworthy that Taiwan and China record the highest citation counts in the field, which may be partly attributable to collaborative publication practices (see Figure 4). International co-authorship has been recognized as a driver of enhanced research quality and visibility. Collaborative publications enable participating scholars to pool complementary expertise, access broader funding opportunities, and increase the impact of their work. Existing research indicates that papers co-authored by researchers from multiple countries tend to receive higher citation rates than those produced within a single country [67], [68]. Hence, the strong citation performance of Taiwan and China may also reflect their engagement in international collaboration networks that enhance scholarly recognition. This prominence is further supported by government investment funds and advanced technological infrastructures [69], [70], which facilitate the production of rigorous research outputs. Such conditions align with prior findings suggesting that higher citation rates are often associated with greater availability of resources for conducting high-quality research [71]. Previous studies have also identified China and Taiwan among the world's top 10 contributors to VAMR research in education, underscoring their prominent role in advancing this field at the global level [17]–[19].

Table 4. Top 10 countries/regions with the most citations

Country/Region	TC	TP	ACP
Taiwan	542	17	31.88
China	515	18	28.61
Turkey	323	10	32.30
Singapore	303	8	37.88
Malaysia	262	25	10.48
Hong Kong	170	7	24.29
United Arab Emirates	169	5	33.80
Saudi Arabia	89	4	22.25
Thailand	76	4	19.00
India	59	9	6.56

In addition, emerging Asian economies such as China, Taiwan, and Singapore have significantly shaped the development of this field, largely due to substantial government funding for technological advancement, which has stimulated research productivity. In contrast, contributions from developing countries, including Bangladesh, Cambodia, Afghanistan, Laos, Myanmar, Timor-Leste, Nepal, and Yemen, remain limited. This disparity underscores the importance of expanding research capacity, fostering international partnerships, and strengthening institutional support in underrepresented regions to promote more inclusive scholarly participation in VAMR-STEMEd research across Asia.



a)

b)

Fig. 4. Country co-authorship networks: (a) all countries, (b) connected countries

Figure 4 illustrates the network visualization of co-authorship among Asian countries in VAMR-STEMEd research. The analysis included all nations with at least one publication, resulting in 22 countries that were grouped into 14 distinct clusters based on their collaboration patterns. In this network, node size reflects the level of collaborative activity of each country, while the thickness of the connecting lines represents the strength of their research partnerships. Also, higher link strength values signify stronger research collaborations between countries. Countries depicted in the same color indicate closer co-authorship relationships within the same cluster.

As can be seen in Figure 4, Malaysia stands out as the most prominent collaborator, with a total link strength (TLS) of 8, demonstrating substantial research connections with Indonesia, China, Hong Kong, and the United Arab Emirates (UAE). TLS indicates the cumulative intensity of a nation's collaborative ties with others, thus serving as an indicator of its integration within the regional research landscape. Specifically, the strongest bilateral collaboration is observed between Malaysia and Indonesia, with a link strength of 3 (Cluster 1, red), followed by the collaboration between China and Taiwan, which has a link strength of 2 (Cluster 3, yellow). Meanwhile, weaker but still notable partnerships are found between the UAE and Saudi Arabia (link strength = 1; Cluster 2, green) and between Hong Kong and Macao (link strength = 1; Cluster 4, blue). The remaining eight clusters each consist of a single country, indicating limited international collaboration with other Asian countries/regions.

4.4 Most Active Institutions

The institutions and their documents in the top 10 positions are shown in Table 5. In terms of research productivity, Nanyang Technological University (NTU) and Universiti Kebangsaan Malaysia (UKM) stand out as the most prolific institutions, each contributing seven publications. This suggests that these universities have established research agendas and institutional support for VAMR studies in STEM education. The strong research output of these institutions can be attributed to their strategic institutional policies and long-term commitments to advancing immersive technologies in STEM education. NTU [72] has established meriSTEM@NIE Singapore, a dedicated center that integrates research, teaching, and outreach in STEM education. This center is supported by a strong collaboration of researchers, academics, and industry partners, enabling interdisciplinary collaboration in immersive technologies. Similarly, UKM demonstrates a strong institutional commitment through the establishment of the STEM Enculturation Research Center, which aligns closely with the National STEM Strategic Action Plan [73]. The center, founded in 2017, was designed to strengthen faculty research capacity in STEM education.

However, when considering total citation impact, National Taiwan Normal University (NTNU) emerges as the most influential affiliation despite having only four publications, accumulating 316 citations, which surpasses all other institutions in the list. This indicates that research produced by this institution is highly recognized and frequently referenced within the scholarly community, reflecting the visibility and quality of its contributions. Furthermore, NTNU also records the highest average number of citations per publication, with an ACP of 79.00, exceeding that of other institutions, including NTU, which, despite its higher publication output, has a lower ACP of 41.14. This pattern suggests that while some institutions prioritize research quantity, others achieve greater scholarly impact through fewer but more influential publications. These trends highlight that NTU and UKM lead in publication volume, whereas NTNU demonstrates the strongest citation performance, both in TC and average citations per document. This underscores NTNU's crucial role in shaping high-impact VAMR-STEMEd research across Asia. These findings reveal that while Malaysia demonstrates the broadest institutional participation with five universities contributing 21 papers (147 citations), Taiwan exhibits a stronger citation influence (568 citations and 12 papers), driven largely by the outstanding performance of

NTNU. This reflects that academic institutions and funders in Malaysia and Taiwan have long recognized the importance of implementing immersive technologies in STEM education.

Table 5. Top 10 institutions with the most publications

Institution	Location	TP	TC	ACP
Nanyang Technological University	Singapore	7	288	41.14
Universiti Kebangsaan Malaysia	Malaysia	7	92	13.14
National Taiwan Normal University	Taiwan	4	316	79.00
National Taiwan University of Science and Technology	Taiwan	4	179	44.75
The Education University of Hong Kong	Hong Kong	4	125	31.25
National Cheng Kung University	Taiwan	4	73	18.25
Universiti Sains Malaysia	Malaysia	4	9	2.25
Universitas Negeri Yogyakarta	Indonesia	4	7	1.75
Universiti Pendidikan Sultan Idris	Malaysia	4	1	0.25
Universiti Teknologi MARA	Malaysia	3	44	14.67
East China Normal University	China	3	40	13.33
Indian Institute of Technology Bombay	India	3	32	10.67
Universiti Malaysia Pahang Al-Sultan Abdullah	Malaysia	3	1	0.33

The relatively high productivity of institutions and the growing impact of citations across Asian countries demonstrate that the integration of VAMR is increasingly supported by mobile infrastructure that enables learning beyond the traditional classroom. Mobile AR and VR technologies enable students to access and interact with virtual content anytime and anywhere, fostering a self-paced, student-centered learning approach [62]. In this context, mobile MR provides opportunities for designing authentic, contextual, and collaborative learning experiences, leveraging features such as sensors, GPS, and integrated cameras embedded in modern devices [74]. The ubiquity of mobile device ownership and the increasing adoption of BYOD strategies further strengthen the relevance of VAMR technologies in enabling learner-generated content [64].

4.5 Most relevant authors

Analysis of the top 10 authors listed in Table 6 reveals that publications are concentrated in a small number of institutions and countries, particularly Singapore and Malaysia. In terms of publication output, three authors (i.e., Yiyu Cai, Lihui Huang, and Yuan Xie) emerge as the most prominent contributors, each affiliated with Nanyang Technological University, Singapore, with three publications and a total of 77 citations. These authors collaborated extensively, with all of their publications appearing in 2024. Their most recent article examines how VR-based educational games influence students' academic knowledge in engineering education [27]. This indicates a relatively recent but impactful contribution from this study group, suggesting that Singapore has become an influential hub for

VAMR-STEMEd research in the most recent period of the dataset. In comparison, Nazatul Aini Abd Majid from Universiti Kebangsaan Malaysia also records three publications, but with a slightly lower total citation count of 73 and an earlier first publication (FP) in 2018, reflecting a long-standing involvement in the field. Meanwhile, Yun Wen, also from Nanyang Technological University, demonstrates a particularly notable scholarly impact despite having only two publications, accumulating the highest TC (159) since her FP in 2021. This suggests that her work has been highly influential and widely referenced within the academic community. More broadly, the distribution of authors shows that four of the top contributors are based in Singapore and three in Malaysia, indicating that Southeast Asia, especially these two countries, plays a leading role in shaping the regional research landscape on VAMR-STEMEd.

Table 6. Top 10 authors with the most publications

Author	Institution	Location	TP	TC	FP
Yiyu Cai	Nanyang Technological University	Singapore	3	77	2024
Lihui Huang	Nanyang Technological University	Singapore	3	77	2024
Yuan Xie	Nanyang Technological University	Singapore	3	77	2024
Nazatul Aini Abd Majid	Universiti Kebangsaan Malaysia	Malaysia	3	73	2018
Danakorn Nincarean Eh Phon	Universiti Malaysia Pahang Al-Sultan Abdullah	Malaysia	3	1	2024
Yun Wen	Nanyang Technological University	Singapore	2	159	2021
Riyan Hidayat	Universiti Putra Malaysia	Malaysia	2	80	2024
Yueh-Min Huang	National Cheng Kung University	Taiwan	2	63	2018
Prachyanun Nilsook	King Mongkut's University of Technology North Bangkok	Thailand	2	59	2016
Somsak Techakosit	Kasetsart University	Thailand	2	59	2016

In this study, Lotka's law was employed to analyze long-term patterns of research productivity and to identify the most prolific authors in the field. Lotka [75] suggests that the number of authors producing a given number of publications is inversely proportional to the number of publications they generate. Figure 5 presents the observed and theoretical distributions based on this principle. The findings indicate that the majority of authors—93.5% (403 individuals)—contributed only one publication. Meanwhile, 5.30% (23 authors) published two papers, and a smaller proportion, 1.20% (5 authors), were involved in three publications. These results demonstrate an inverse relationship between publication output and the number of contributing authors, whereby higher productivity is associated with a smaller group of researchers. As Lotka's law provides a robust framework for assessing scholarly productivity over time, the observed pattern suggests that studies on VAMR-STEMEd continue to attract widespread engagement from both academic researchers and educational practitioners. The authorship distribution offers meaningful insights into collaboration patterns and knowledge production within this evolving research domain.

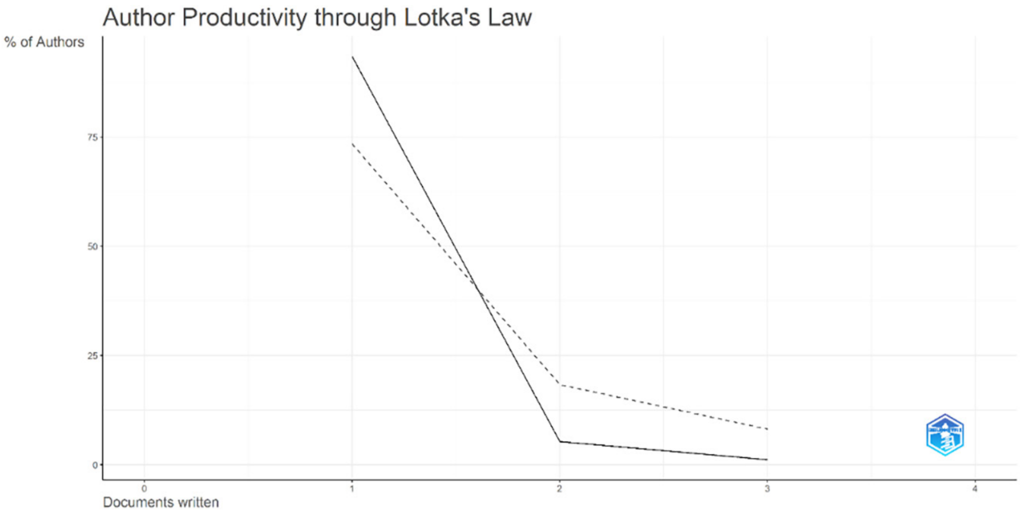


Fig. 5. Lotka's law

A co-authorship analysis was conducted to determine the most influential body of work and the extent of collaborative relationships among scholars [59]. This bibliometric technique explores research collaboration by examining joint authorship patterns across journal publications, thereby revealing intellectual and social connections within the field. The co-authorship network, visualized using VOSviewer based on author names, consists of 13 unique clusters, as presented in Figure 6.

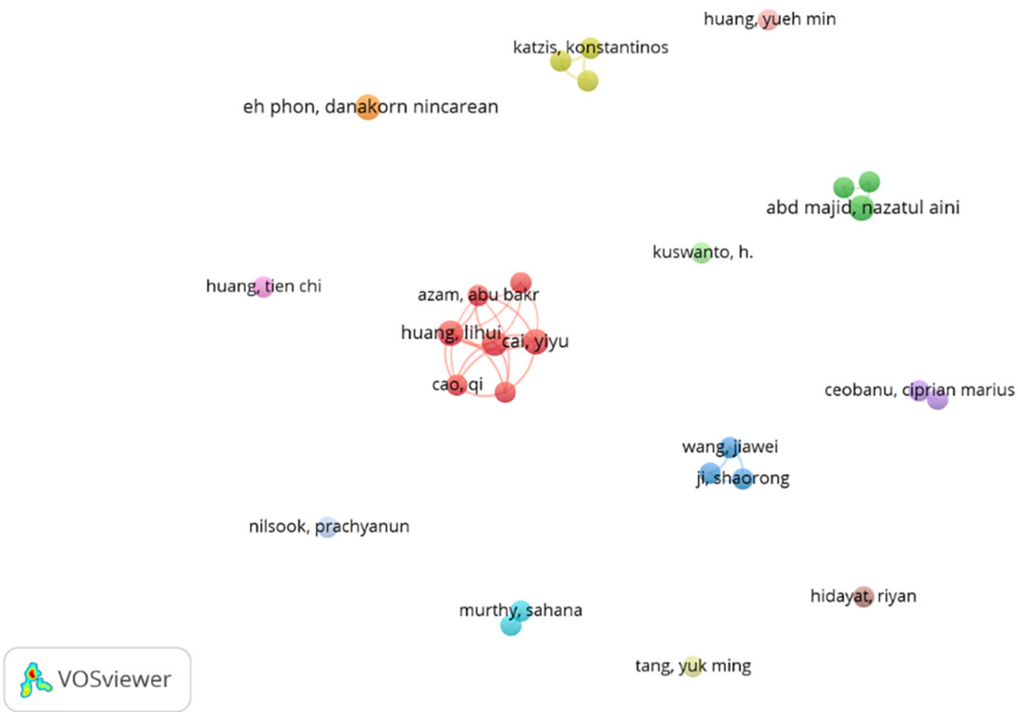


Fig. 6. Co-authorship of authors

The visualization includes 27 authors who have each published at least two articles, where each node represents an individual author and its size corresponds to their number of publications. Authors are grouped into distinct clusters based on the strength of their collaborative ties. Each author belongs to only one cluster in the network.

For example, Lihui Huang from Nanyang Technological University, positioned in Cluster 1 (red), is associated with six links, a TLS of 13, three publications, 77 citations, and an average publication year of 2024. In Cluster 2 (green), Nazatul Aini Abd Majid from Universiti Kebangsaan Malaysia has two links, a link strength of two, three publications, 73 citations, and an average publication year of 2020.67. Meanwhile, Jiawei Wang from Universiti Sains Malaysia, classified in Cluster 3 (dark blue), has two links, a link strength of four, two publications, and an average publication year of 2025. Figure 6 demonstrates the emergence of several independent author groups, indicating limited cross-cluster collaboration. This pattern suggests that global research networks on VAMR-STEMEd remain fragmented and relatively small. These findings highlight the significant potential for international collaboration in future studies.

4.6 Most prolific journals

The top 10 most influential journals in VAMR-STEMEd research in Asia are shown in Table 7. The table summarizes the number of citations and papers published in each source. Among the top 10, *Education and Information Technologies* (published by Springer, ranked in Q1, H = 4, FP = 2024) emerges as the most productive venue with the highest number of publications (TP = 5). This indicates that this journal has recently become a preferred platform for disseminating VAMR studies, likely due to its broad scope at the intersection of education and digital technologies. The high H-index (H) reflects the high impact of *Education and Information Technologies* in this field [76]. In terms of total citation impact, *Electronics (Switzerland)* (an open-access (OA) journal published by MDPI, H = 3, FP = 2023) records the highest (TC = 266) and also the highest average citations per paper (approximately 89 citations per paper). This shows that despite being ranked in Q2, articles published in *Electronics (Switzerland)* have received substantial attention from researchers within a short period of time. One plausible explanation is the OA publishing model adopted by the journal. As mentioned by Piwowar et al. [77], OA articles tend to be viewed and cited more frequently than those published in subscription-based journals. The OA movement seeks to ensure that scholarly outputs are freely and permanently available to a global audience, thereby reducing access barriers and expanding knowledge dissemination.

Table 7. Top 10 journals with the most citations

Journal	TC	TP	H	Q	Publisher	FP
Electronics (Switzerland)	266	3	3	Q2	MDPI	2023
Interact. Learn. Environ.	223	4	3	Q1	Routledge	2022
Educ. Technol. Res. Dev.	158	3	2	Q1	Springer	2021
Comput. Hum. Behav.	148	2	2	Q1	Elsevier	2015
Educ. Inf. Technol.	137	5	4	Q1	Springer	2024
Smart Learn. Environ.	119	2	2	Q1	Springer	2020
IEEE Trans. Learn. Technol.	111	1	1	Q1	IEEE	2023
Res. Pract. Technol. Enhanc. Learn.	103	1	1	Q1	Springer	2017
J. Comput. Assisted Learn.	101	3	1	Q1	Blackwell Publishing	2020
Informatics	88	1	1	Q1	MDPI	2022

Note: quartile (Q).

Following this, *Interactive Learning Environments* (Routledge, Q1, H = 3, FP = 2022) represents a strong balance between productivity and impact (TP = 4; TC = 223). It can be said that this journal plays a central role in research on interactive and immersive learning technologies. Meanwhile, *Educational Technology Research and Development* (Springer, Q1, H = 2, FP = 2021) demonstrates consistent influence (TP = 3; TC = 158) as a well-established outlet in the field. These patterns indicate a dual publication trajectory. Journals focused on education and technology and in the high Q, particularly *Education and Information Technologies* and *Interactive Learning Environments*, dominate in terms of research dissemination. In contrast, technology-oriented journals, particularly *Electronics (Switzerland)*, lead in citation counts. This suggests that VAMR-STEMEd studies tend to attract cross-disciplinary attention. The relatively recent FP years (2021–2024) of most leading journals further demonstrate that VAMR in STEM education in Asia is a growing research field. This is characterized by increasing research output, increasing citation visibility, and a gradual shift towards high-impact publication venues.

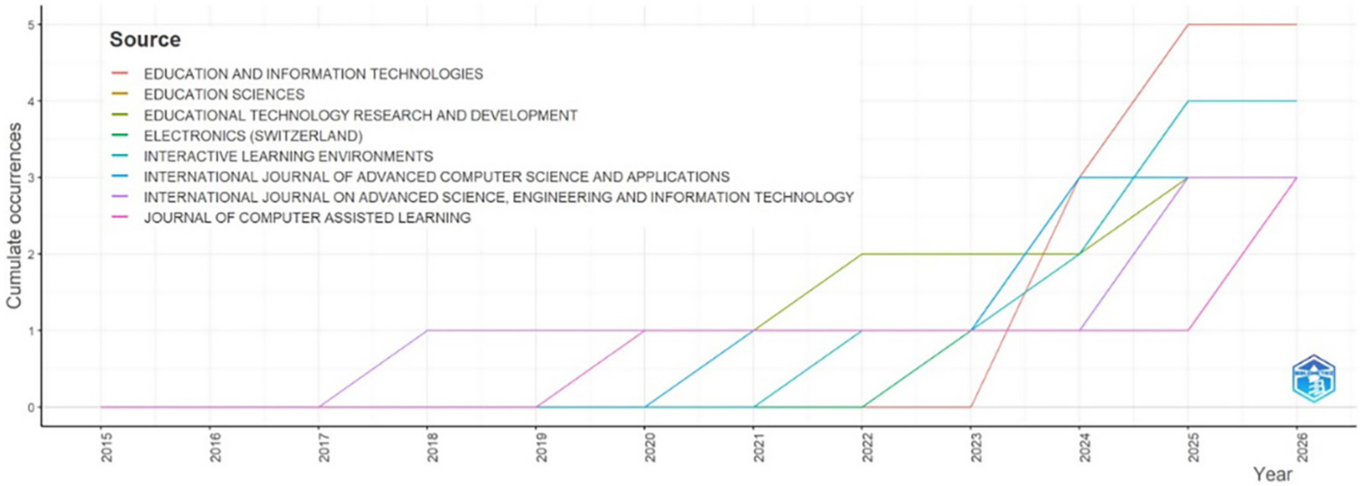


Fig. 7. Journals' production (cumulative) over time

Figure 7 shows a clear upward trend in the number of publications from the most productive sources (with a minimum of three documents), particularly from 2018 onward. Among these sources, the *International Journal on Advanced Science, Engineering, and Information Technology* was the first to publish studies on VAMR-STEMEd in 2018, marking an early engagement with this study area. In contrast, *Education and Information Technologies* have demonstrated the fastest growth in publication output over time. This indicates increasing scholarly interest and expanding contributions to this field.

To identify the most influential publication outlets in this field, a Bradford analysis using the Bibliometrix package in R was conducted. By applying Bradford's law [78], the core journals that have played a central role in shaping scholarly discourse on VAMR-STEMEd in Asia can be identified (see Figure 8). The analysis revealed that the 122 documents in the dataset were distributed across 87 different journals, with individual publication counts ranging from one to five articles. Based on Bradford's law, these journals were categorized into three distinct zones according to their contribution to the literature, with Zone 1 representing the most impactful sources. The Bradford core (Zone 1) comprised 15 journals (17.24% of all sources), which accounted for 41 publications (33.61% of the total documents). Zone 2 included

32 journals (36.78%) that also contributed 41 articles (33.61%), while Zone 3 contained the largest number of sources—40 journals (45.98%)—but produced slightly fewer papers, totaling 40 documents (32.79%).

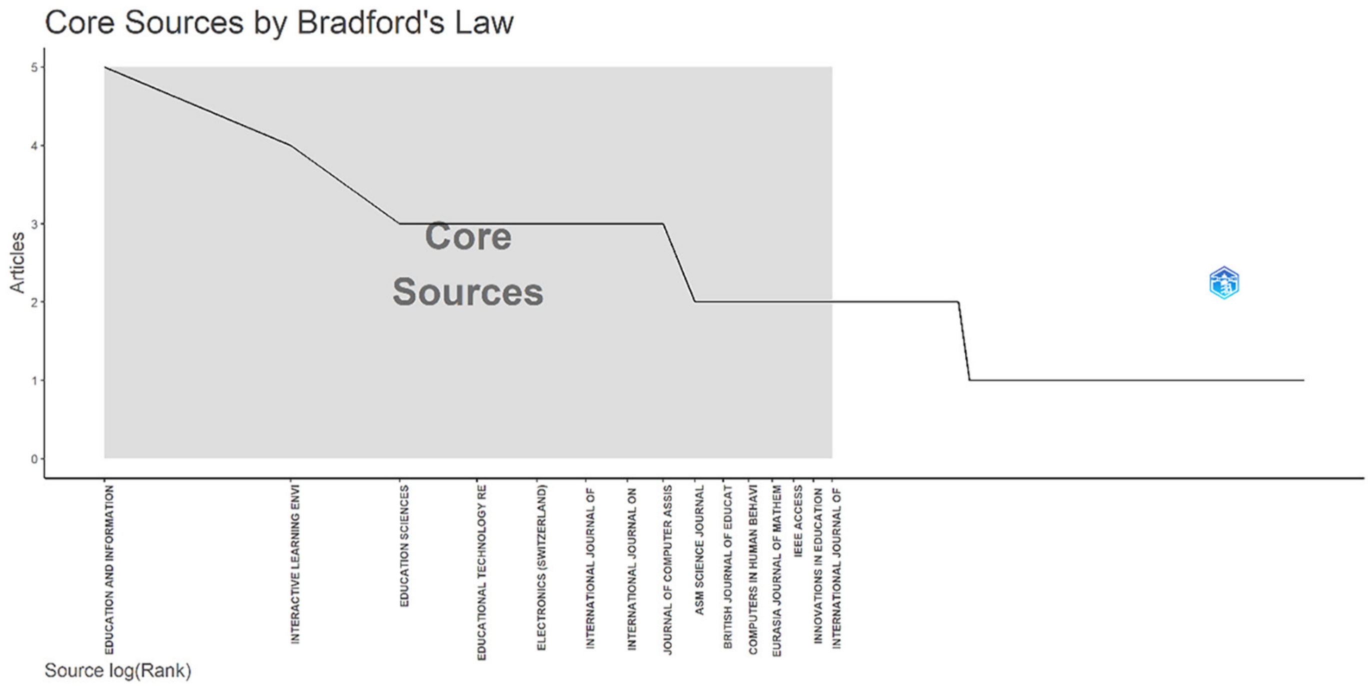


Fig. 8. Bradford's law

4.7 Frequently cited documents

The frequently cited documents in the first 10 positions are listed in Table 8. In the first place, the study by AlGerafi et al. [36], published in *Electronics (Switzerland)* (MDPI, ranked in Q2, SJR 0.615) with 237 citations, serves as a comprehensive synthesis of empirical and conceptual work on AR and VR across multiple educational domains, including K-12 and STEM education. The authors aimed to examine how AR and VR contribute to improved learning outcomes, knowledge retention, and skill acquisition. Their findings highlight the potential of immersive technologies while offering practical recommendations for educators regarding effective implementation, instructional design, and integration into existing curricula. This work is influential because it bridges technological innovation with educational practice, positioning VAMR as a novel tool that provides a meaningful learning environment for students. Moreover, the high citation count of this study may also be associated with its publication in an OA journal, which tends to increase visibility and scholarly impact compared to non-OA publications [77].

The second most cited document, by Sırakaya and Sırakaya [43] in *Interactive Learning Environments* (published by Routledge, Q1, SJR 1.976), with 183 citations, provides a focused review of AR applications specifically within STEM education. By analyzing 42 journal articles, the study reveals that research on AR in STEM has intensified in recent years and is predominantly situated in formal school settings such as classrooms and laboratories. The authors found that most implementations relied on marker-based AR. This work shows that most AR technology is applied to

K-12 classrooms. The high citation impact of this work can be attributed to the influential role of review articles, which are generally cited more frequently than other publication types [79]. Review articles provide systematic syntheses of existing studies, consolidate current knowledge, and identify directions for future research [80].

The third highly cited work, by Wen [39], published in *Educational Technology Research and Development* (Springer, Q1, SJR 1.429) with 128 citations, developed an AR-supported Chinese character learning game for young learners. Unlike the broader reviews of AlGerafi et al. [36] and Sırakaya and Sırakaya [43], Wen's study provides empirical evidence of how AR can shape cognitive engagement in authentic learning contexts. The results demonstrate that AR-supported activities significantly enhanced students' cognitive engagement.

Table 8. Top 10 most cited papers

Paper	Authors	Journal	TC	Q	SJR
[36]	AlGerafi et al.	*Electronics (Switzerland)*	237	Q2	0.615
[43]	Sırakaya & Sırakaya	*Interact. Learn. Environ.*	183	Q1	1.976
[39]	Wen	*Educ. Technol. Res. Dev.*	128	Q1	1.429
[81]	Chen et al.	*IEEE Trans. Learn. Technol.*	111	Q1	1.071
[47]	Hsu et al.	*Res. Pract. Technol. Enhanc. Learn.*	103	Q1	0.865
[29]	Chen et al.	*J. Comput. Assisted Learn.*	100	Q1	2.000
[42]	Çeken & Taskin	*Smart Learn. Environ.*	93	Q1	2.476
[14]	Kuhail et al.	*Informatics*	88	Q1	0.651
[60]	Wang et al.	*Comput. Hum. Behav.*	84	Q1	2.923
[38]	Hidayat & Wardat	*Educ. Inf. Technol.*	80	Q1	1.654

Note: SCImago Journal Rank 2024 (SJR).

4.8 Word analysis

Research themes and hot topics. In bibliometric studies, keyword analysis plays a crucial role in revealing the substantive focus and intellectual structure of a research field, as it reflects the core concepts and emerging interests within the literature [55]. To map the principal research themes underpinning the rapid development of VAMR-STEMEd, this study analyzed the most frequently occurring keywords using VOSviewer [59]. Out of 387 identified keywords, 59 met the minimum threshold of at least two occurrences and were subsequently included in the co-occurrence network, as presented in Figure 9a. The network comprises 59 nodes and 204 links, with a TLS of 308, indicating the overall level of connectedness among the keywords. These nodes are organized into 12 distinct clusters, each visually differentiated by color to represent thematic groupings. In this visualization, the size of each node represents the frequency of keyword co-occurrence. Larger nodes, therefore, indicate more prominent terms within the field. The connecting lines illustrate the relationships between keywords based on their joint appearance in publications [59]. TLS indicates the extent to which a keyword is associated with other terms, thus highlighting its central role in the VAMR-STEMEd research landscape.

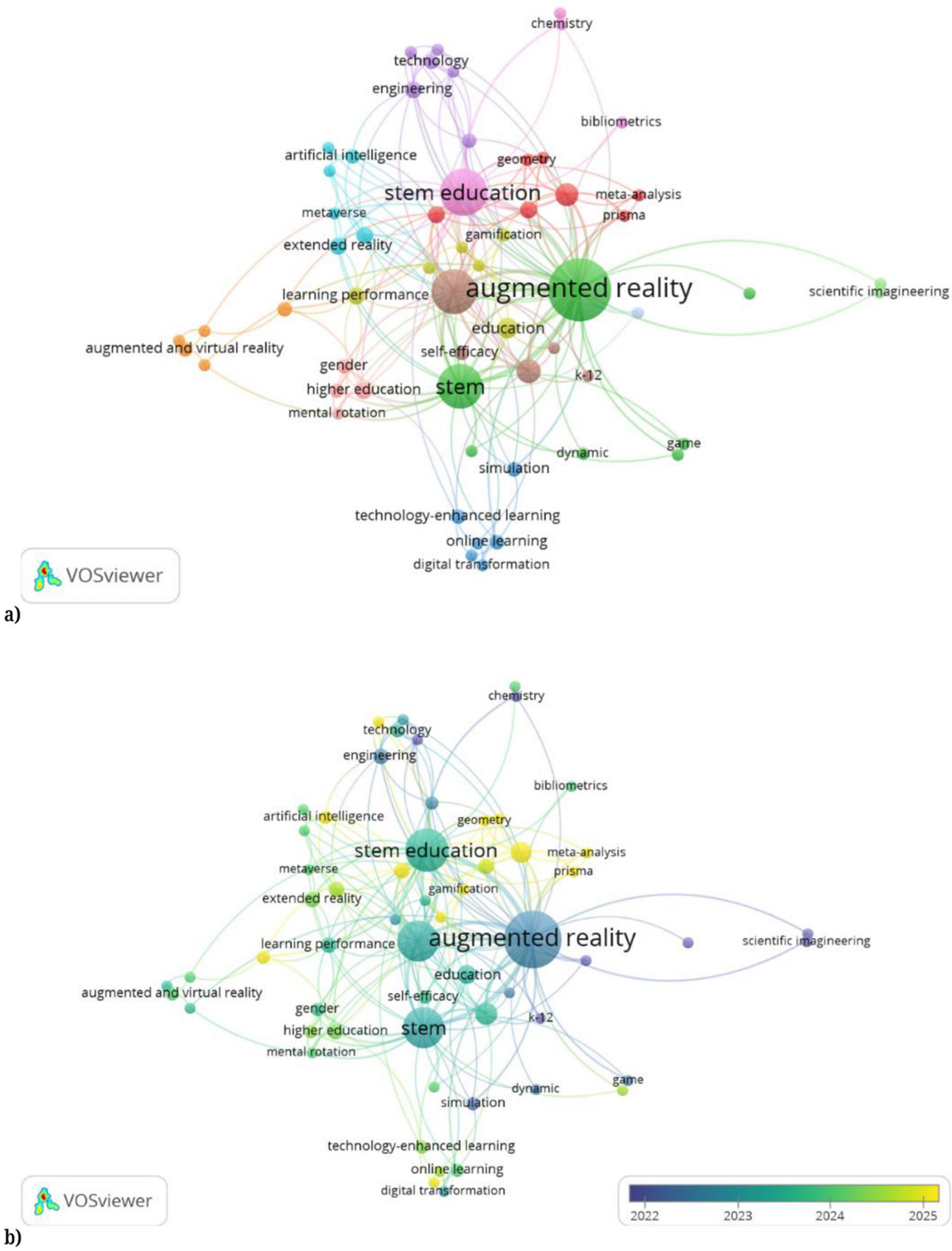


Fig. 9. Keyword co-occurrence map: (a) network visualization and (b) overlay visualization

The first cluster (7 keywords, in red) includes keywords such as "educational technology," "geometry," "learning outcomes," "mathematics education," "meta-analysis," "PRISMA," and "student engagement." This cluster centers on digital pedagogy in mathematics education, particularly the use of educational technology to improve learning outcomes. The inclusion of "meta-analysis" and "PRISMA" indicates a strong methodological emphasis on synthesizing prior empirical studies. The keyword "student engagement" highlights attention to learners' cognitive and affective engagement in technology-supported instruction. For example, Adnan et al. [41] emphasized the development and usability evaluation of

AR-based instructional modules, particularly for secondary mathematics teachers. The results showed that well-designed AR materials can effectively support online learning environments.

The second cluster (7 keywords, in green) features terms including "augmented reality," "critical thinking," "game," "learning experience," "learning motivation," and "STEM." It is characterized by a theme of interactive learning through AR in STEM contexts. Keywords such as AR and games indicate interactive learning environments, while learning motivation and learning experiences highlight students' affective and psychological dimensions. Critical thinking further indicates that these immersive tools are not merely for engagement but are intended to foster students' 21st-century skills. The main research focus of this cluster lies in examining how AR game-based learning environments can enrich the STEM learning process and stimulate students' learning motivation and support their thinking skills. In this context, Lasica et al. [44] highlighted the benefits of AR-supported instructional approaches in STEM-related courses, reporting increased student motivation toward the learning process.

The third cluster (6 keywords, in dark blue) encompasses keywords related to "bibliometric analysis," "digital transformation," "distance education," "online learning," "simulation," and "technology-enhanced learning." It revolves around a theme of digital transformation in contemporary STEM education, particularly in relation to distance and online learning. The inclusion of bibliometric analysis suggests an evaluation of research trends, while simulation and technology-enhanced learning underscore the role of digital tools in mediating remote educational experiences. This cluster focuses on how technological advancements are reshaping educational practices, with particular attention to how virtual simulations and online platforms support the quality of learning in digital learning environments. For instance, Boztas et al. [82] underscored the potential of digital technologies in addressing accessibility challenges and strengthening student engagement.

The fourth cluster (6 keywords, in yellow) includes "education," "gamification," "immersive learning," "interactive learning environment," "learning performance," and "virtual reality." It centers on a theme of immersive and gamified learning environments aimed at improving students' learning performance. The convergence of VR, immersive learning, and interactive learning environments indicates a strong emphasis on experiential pedagogies. Gamification further indicates that game design elements are integrated to maintain students' interest. The research focus of this cluster is primarily on investigating how VR-based and gamified instructional designs can elevate academic performance in STEM disciplines. Alnuaimi and Awad [32], for example, focused on VR gamification applications. They revealed that students exposed to immersive VR environments significantly outperformed those in traditional environments. Furthermore, most undergraduate students reported that the immersive experience was enjoyable and improved their conceptual understanding.

The fifth cluster (six keywords, in purple) comprises keywords such as "engineering," "science," "science education," "scientific literacy," "teacher professional development," and "technology." The presence of science, science education, and scientific literacy highlights a commitment to developing students' understanding of scientific concepts. Meanwhile, teacher professional development (TPD) reflects attention to educators' readiness to implement innovative tools. This cluster is concerned with how technological innovations can support both student learning and teacher competency, thereby strengthening the quality of STEM education. Recently, Mufit et al. [83] integrated AR with a cognitive conflict model within STEM instruction, demonstrating significant improvements in students' scientific literacy.

The sixth cluster (six keywords, in blue) consists of terms like "artificial intelligence," "extended reality," "metaverse," "mixed reality," "science practices," and "virtual environment." It reflects a forward-looking theme of convergent, intelligent, and immersive environments in STEM learning. The integration of artificial intelligence (AI), extended reality (XR), mixed reality, metaverse, and virtual environments suggests an emerging hybrid educational landscape where intelligent systems and immersive technologies intersect. The inclusion of science practices indicates that these environments are intended to simulate authentic scientific inquiry. This cluster focuses on exploring how AI-driven XR environments and metaverse platforms can transform the nature of scientific learning and practice in digital spaces. Supportively, Rehman et al. [84] explored the convergence of AI and MR technologies to enhance engineering students' technical English proficiency. They reported statistically significant gains as well as increased engagement, confidence, and conceptual understanding.

In addition, Clusters 7 to 12 each contain between one and five keywords. This indicates the presence of more specialized and emerging sub-themes within the broader research landscape.

The keyword analysis highlights the dominant thematic focus of VAMR research in STEM education across Asia. The five most prevalent keywords are "augmented reality" (53 occurrences; [TLS] = 102; Cluster 2), "STEM education" (30 occurrences; TLS = 58; Cluster 9), "STEM" (26 occurrences; TLS = 54; Cluster 2), "virtual reality" (26 occurrences; TLS = 40; Cluster 8), and "systematic review" (8 occurrences; TLS = 22; Cluster 8). The prominence of these terms underscores the central role of VAMR technologies in shaping contemporary STEM education research, alongside a growing scholarly interest in synthesizing existing evidence through literature reviews. The results are consistent with the previous literature [25], [37].

Figure 9b illustrates the temporal evolution of research themes through an overlay visualization of the author keyword map for VAMR-STEMEd in Asia. This visualization technique is particularly valuable for detecting emerging trends, as it categorizes keywords based on the mean publication year of the documents in which they appear. Earlier themes are depicted in blue, whereas more recent topics are represented in yellow, allowing for a clear chronological distinction. The results reveal a noticeable shift in scholarly attention toward themes such as "educational technology," "scientific literacy," "immersive virtual reality," "artificial intelligence," "student engagement," and "gamification." This trend suggests that recent research is increasingly oriented toward interactive and learner-centered approaches in STEM education. Recently, the study by Ragab et al. [85] examined students' perceptions of their engagement with interactive technologies such as AI and VR in STEM classrooms. The study revealed significant increases in engagement. The findings further indicate that integrating such technologies can positively influence learning experiences.

The dominance of themes such as "augmented reality" and "virtual reality" reflects the increasing ease of implementing these technologies through mobile devices. AR, in particular, is commonly delivered via smartphone applications that are portable, cost-effective, and widely accessible [74]. The increasing use of mobile devices, supported by decreasing hardware and software costs [63], has significantly expanded their role in STEM education, enabling the integration of multimedia-enriched 3D content into authentic learning contexts [62]. These affordances demonstrate that the increase in VAMR publications is related to the evolution of mobile learning technologies [65], where smartphones and tablets function as primary gateways for interactive STEM learning experiences.

Thematic development. Figure 10 illustrates a multi-field visualization mapping the relationships among the top 10 journals, author keywords, and authors. In this three-panel representation, journals are displayed on the left, author keywords occupy the central field, and contributing authors are positioned on the right, enabling a clear overview of their interconnections. The visualization highlights several dominant keywords within the dataset, most notably "Augmented Reality," "STEM Education," "Higher Education," "STEM," and "Virtual Reality," indicating their central role in shaping research within this domain. The analysis further shows that *Education and Information Technologies* emerges as the most influential journal, demonstrating strong linkages with nearly all of the top-ranked keywords. Other prominent outlets, including *Interactive Learning Environments* and *Education Sciences*, also contribute substantially to keyword-related publications, albeit to a lesser extent. Among these journals, *Education and Information Technologies* makes the most significant contribution to studies associated with the keyword "Augmented Reality," although meaningful contributions are also observed from other sources. Moreover, the examination of keyword-author relationships reveals that the majority of authors employ the terms "Augmented Reality" and "STEM Education" in their publications, suggesting a shared thematic focus across the field.

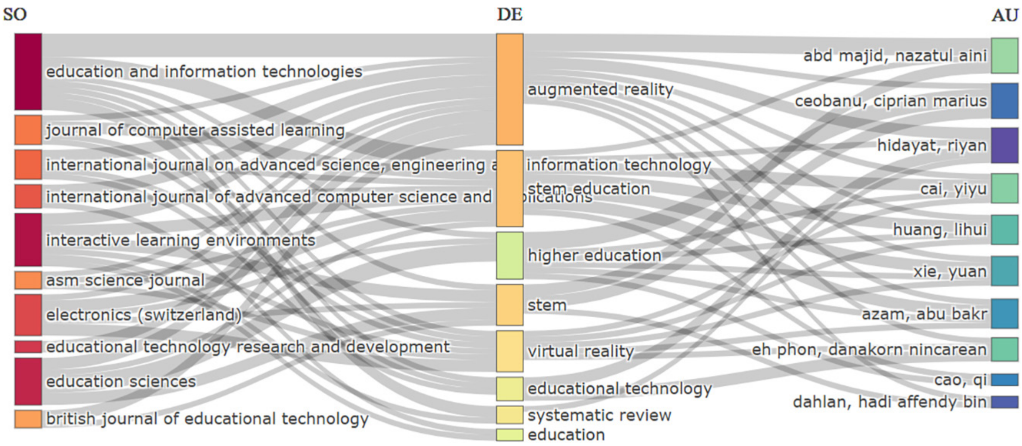


Fig. 10. Three-field plot: journals (left), author keywords (middle), authors (right)

Thematic evolution. Figure 11 visualizes the thematic evolution of VAMR-STEMEd research in Asia from 2015 to 2026, mapping the shifting and expanding scholarly focus over four consecutive periods. The figure highlights key themes such as "virtual reality," "augmented reality," "extended reality," and "STEM." Over the years, these themes have evolved and interconnected. In the initial phase (2015–2020), the thematic landscape is predominantly technology-centered, with "virtual reality" and "augmented reality" emerging as the two primary research streams. This reflected early explorations of their potential in educational contexts. During 2021–2022, the focus became more consolidated around augmented reality while also branching into "education" and "systematic review." In the 2023–2024 period, the concept of "extended reality" gained prominence, signaling a conceptual integration of virtual, augmented, and mixed reality while maintaining strong links to augmented reality. Finally, in 2025–2026, the thematic trajectory converges toward "STEM," demonstrating a maturation of the field in which immersive technologies are no longer treated as standalone innovations but are embedded within STEM education research in Asia. The consistent presence of "augmented reality" across all periods implies its foundational role in education.

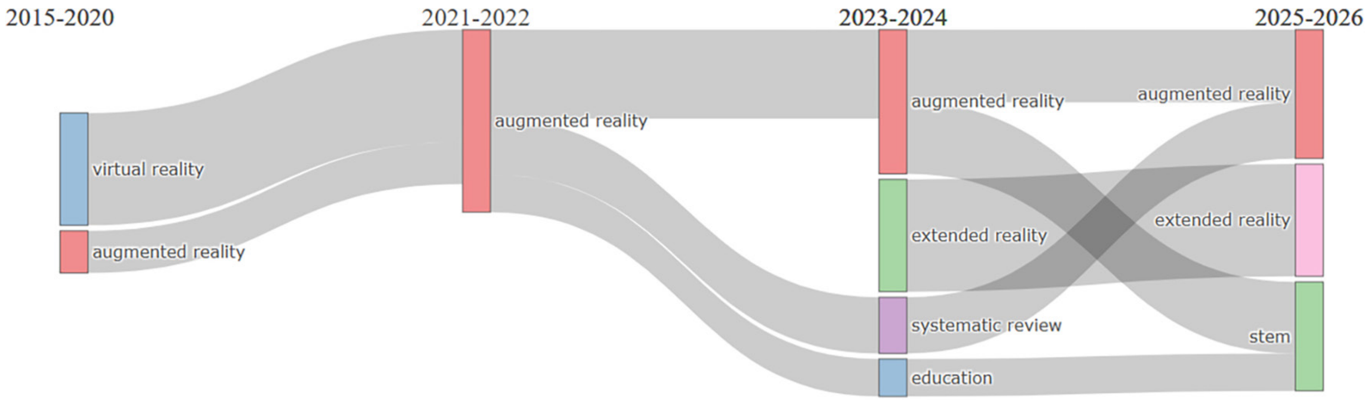


Fig. 11. Thematic evolutions

Thematic map. According to the author keywords, a thematic map was generated using Bibliometrix (see Figure 12) to illustrate the intellectual structure and thematic development of research on VAMR-STEMEd in Asia [58]. This visualization categorizes research themes into four quadrants (i.e., motor, niche, emerging or declining, and basic) based on their levels of centrality and density. It thereby provides a deeper understanding of how different topics contribute to and shape the field. The analysis reveals that themes positioned in the *emerging or declining themes* (lower-left), such as "chemistry," "embodied learning," and "learning motivation," exhibit low centrality and density. This indicates that they remain marginal and underdeveloped within VAMR-STEMEd research and have not yet established strong connections with the broader field. However, examination of publication timelines indicates that studies addressing these themes are just beginning to appear in the literature [26], [86]. This temporal pattern suggests that these topics are more likely to be categorized as emerging themes rather than declining themes. Positioned within this theme, Mira et al. [86] analyzed embodied collaborative learning in extended reality contexts, identifying positive impacts on social interactivity, collaboration quality, academic performance, and social flow.

In contrast, themes located in the *basic themes* (lower-right), including "augmented reality," "STEM education," "higher education," "learning performance," and "gender," demonstrate high centrality but relatively low density. This suggests that these topics are foundational, widely connected to other areas of research, and essential for structuring the field, even though their theoretical and methodological development is still evolving. For example, Anh [45] investigated the effects of mobile AR applications on Vietnamese middle school students' astronomy competencies. The study found improvements in short-term learning outcomes and suggested potential contributions to reducing gender disparities in STEM participation.

Meanwhile, *niche themes* in the upper-left quadrant, such as “online learning,” “technology-enhanced learning,” “scientific imagineering,” and “STEM literacy,” display high internal coherence but limited integration with the broader VAMR research landscape. This implies that while these areas are well-developed in their own right, they remain somewhat peripheral and would benefit from stronger conceptual and empirical alignment with mainstream VAMR studies. In an empirical study, Jin et al. [34] developed a VR teaching system for undergraduate beginners in drone operation. They reported that immersive VR instruction effectively fostered STEM literacy.

Finally, the *motor themes* in the upper-right quadrant, including “engineering,” “science education,” “technology,” “human-computer interface,” “educational technology,” “learning outcomes,” “gamification,” and “virtual reality,” exhibit both high centrality and high density. This indicates that they are not only well-established but also highly influential in driving the advancement of VAMR-STEMEd across Asia. For example, Hung et al. [33] examined the integration of online collaboration scripts within VR-based co-creation learning during distance education. They demonstrated that structured collaborative scaffolding in immersive environments significantly enhanced students’ learning achievement and communication skills.

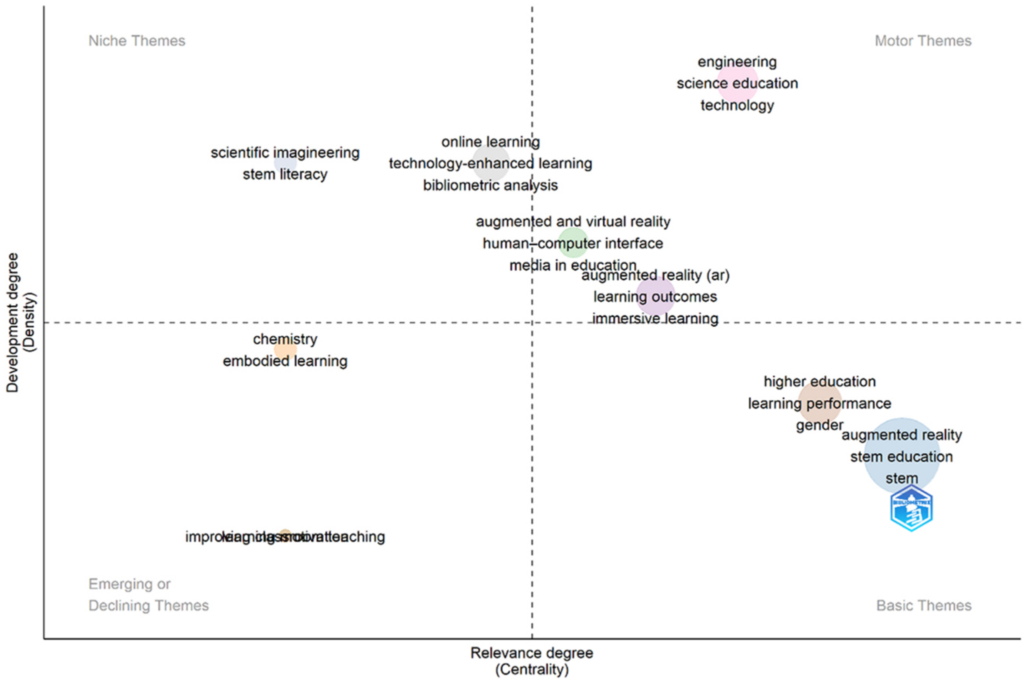


Fig. 12. Thematic map

Conceptual structure. Figure 13 presents a multiple correspondence analysis (MCA) of author keywords, where Dimension 1 (22.05%) and Dimension 2 (14.60%) together explain 36.65% of the total variance and form a single dominant thematic cluster. The axes capture the principal directions of semantic variation in VAMR-STEMEd research. The spatial distribution of terms reflects their frequency and co-occurrence patterns. Keywords positioned closer together on the conceptual structure map indicate stronger conceptual proximity and thematic alignment.

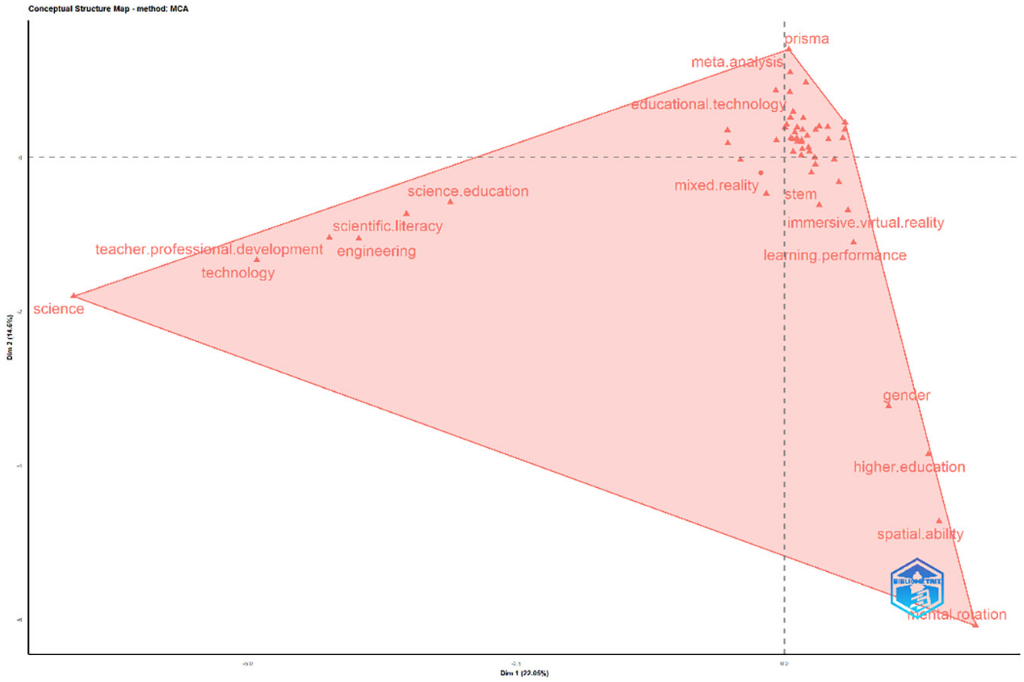


Fig. 13. Factorial analysis

The red cluster spans a broad conceptual domain and includes closely interconnected terms such as "educational technology," "mixed reality," "immersive virtual reality," "augmented reality," "STEM education," "scientific literacy," and "higher education." This configuration suggests a strong research emphasis on integrating immersive technologies into STEM pedagogy across both K-12 and higher education. Additionally, the central proximity of terms such as "gamification," "mixed reality," "virtual reality," and "learning performance" indicates their role as pivotal concepts linking major research strands. In contrast, more isolated terms, such as "mental rotation" (bottom right corner), may represent either specialized thematic niches or emerging research directions that remain less integrated within the broader theoretical and conceptual framework of the field.

5 IMPLICATIONS OF THE STUDY

This bibliometric review provides several practical implications for advancing VAMR integration in STEM education across Asia. Given that VAMR technologies can enhance students' academic achievement and communication skills [33], [87], cognitive engagement [39], conceptual understanding [32], inquiry skills [60], STEM literacy and computational thinking [34], and STEM interest [47], educators and researchers should integrate VAMR with pedagogical approaches that address diverse learner needs. In particular, VAMR can facilitate experimental instruction and inquiry-based activities, making abstract STEM concepts more tangible and accessible while enriching students' learning experiences. To maximize these benefits, TPD training is essential [44]. Educational institutions should establish teacher learning communities to reduce barriers to VAMR integration and implement TPD training programs that strengthen both technical proficiency and pedagogical design for VAMR-supported STEM instruction. At the same time, technology developers are urged to design user-friendly platforms and simplify implementation processes to facilitate adoption in educational settings. Given the rapid advancement of AI [84], [85], future research should explore AI-embedded VAMR applications and examine their impact on learners' 21st-century skills. At the institutional and policy levels, adequate investment in infrastructure, the development of VAMR-based STEM laboratories, and targeted funding for under-resourced schools are critical to ensuring equitable access and reducing educational disparities. In particular, for policymakers in developing economies, mobile learning that leverages student-owned devices offers a cost-effective strategy for integrating mobile AR, VR, and MR into STEM education [63]. While high-end immersive VR headsets and high-performance computers may be constrained by cost and infrastructure requirements, low-cost mobile devices, such as portable smartphone-based VR, offer more feasible solutions for educational institutions [62]. The integration of mobile AR, VR, and MR applications into STEM education supports the development of authentic simulations, gamified learning experiences, and real-world learning environments, thereby enhancing student engagement and learning outcomes. In short, these efforts can foster a more inclusive and innovative STEM education while providing a comprehensive reference point for Asian scholars seeking to understand and further develop the VAMR-STEM research landscape.

6 CONCLUSIONS

This bibliometric review aimed to map and analyze research trends on VAMR in STEM education across Asia from 2015 to 2026 from the Scopus database. The findings reveal a consistent increase in publication output and citation impact over the past decade. This indicates that VAMR integration in STEM education has become an emerging research domain. The analysis highlights dominant contributions from high-income economies, particularly Taiwan, China, Singapore, and Hong Kong. These countries/regions occupy central positions in collaboration networks and demonstrate strong research productivity and citation impact, with Taiwan leading in citation counts, followed by China, Turkey, and Singapore. Although multi-authored publications predominate and collaboration is increasing, partnerships remain largely domestic. This suggests the need to strengthen cross-national research cooperation to promote more balanced regional development. Leading authors and institutions are primarily based in Singapore, Malaysia, Taiwan, and Hong Kong. In addition, influential publication venues, such as *Electronics (Switzerland)* and *Interactive Learning Environments*, reflect the interdisciplinary nature of VAMR-STEMEd, spanning education, technology, computer science, psychology, and informatics. Frequently occurring keywords, including "augmented reality," "virtual reality," "STEM education," "STEM," and "systematic review," further underscore the technological orientation of this field. This study provides a comprehensive intellectual and structural overview of VAMR-STEMEd research in Asia, offering insights into publication patterns, collaboration characteristics, and thematic evolution. These findings contribute a valuable reference framework for Asian scholars, practitioners, and policymakers by clarifying the field's developmental trajectory, identifying research hotspots, and informing future research directions and strategic collaborations.

7 LIMITATIONS AND FUTURE RESEARCH

Although this study provides a comprehensive overview of the most relevant literature on VAMR-STEMEd in Asia, several limitations must be acknowledged. The analysis was confined to journal articles indexed in the Scopus database, which may have restricted the scope of the review. Consequently, relevant studies published in other databases, such as Web of Science, and documents published in local or regional journals were not included. This restriction may have resulted in the omission of relevant and influential studies. Future research can extend this work by incorporating multiple databases to achieve broader coverage of the literature and minimize potential selection bias. Lastly, this review did not incorporate grey literature, including theses, dissertations, working papers, and non-indexed reports, which could offer practical and contextual insights but are challenging to collect and analyze systematically. These limitations do not invalidate the findings of the study; however, they should be considered when interpreting the results and their broader applicability.

8 ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Not applicable. There are no human participants or animal subjects in this paper, and therefore, informed consent is not required.

9 REFERENCES

[1] N. Behnamnia, A. Kamsin, M. A. B. Ismail, and S. A. Hayati, "Relationship between creative thinking and outcomes in a digital STEM-based learning environment: A mixed methods case study," *Think. Ski. Creat.*, vol. 57, pp. 1–30, 2025. https://doi.org/10.1016/j.tsc.2025.101816

[2] I. Govender, "Digital literacy and STEM skills–What is the connection? A systematic review," *Technol. Knowl. Learn.*, pp. 1–22, 2025. https://doi.org/10.1007/s10758-025-09879-x

[3] I. Irwanto, A. D. Saputro, W. Widiyanti, M. F. Ramadhan, and I. R. Lukman, "Research trends in STEM education from 2011 to 2020: A systematic review of publications in selected journals," *Int. J. Interact. Mob. Technol.*, vol. 16, no. 5, pp. 19–32, 2022. https://doi.org/10.3991/ijim.v16i05.27003

[4] X. Gu, D. Tong, P. Shi, Y. Zou, H. Yuan, and C. Chen, "Incorporating STEAM activities into creativity training in higher education," *Think. Ski. Creat.*, vol. 50, pp. 1–13, 2023. https://doi.org/10.1016/j.tsc.2023.101395

[5] E. Hiğde and H. Aktamış, "The effects of STEM activities on students' STEM career interests, motivation, science process skills, science achievement and views," *Think. Ski. Creat.*, vol. 43, pp. 1–13, 2022. https://doi.org/10.1016/j.tsc.2022.101000

[6] A. T. Akcan, B. Yıldırım, A. R. Karataş, and M. Yılmaz, "Teachers' views on the effect of STEM education on the labor market," *Front. Psychol.*, vol. 14, pp. 1–11, 2023. https://doi.org/10.3389/fpsyg.2023.1184730

[7] M. Andrée and L. Hansson, "Industrial actors and their rationales for engaging in STEM education," *J. Curric. Stud.*, vol. 52, no. 4, pp. 551–576, 2020. https://doi.org/10.1080/00220272.2019.1682055

[8] X. Cao, H. Lu, Q. Wu, and Y. Hsu, "Systematic review and meta-analysis of the impact of STEM education on students learning outcomes," *Front. Psychol.*, vol. 16, pp. 1–15, 2025. https://doi.org/10.3389/fpsyg.2025.1579474

[9] T. Roberts *et al.*, "Students' perceptions of STEM learning after participating in a summer informal learning experience," *Int. J. STEM Educ.*, vol. 5, pp. 1–14, 2018. https://doi.org/10.1186/s40594-018-0133-4

[10] M. Ammar, N. J. Al-thani, and Z. Ahmad, "Role of pedagogical approaches in fostering innovation among K-12 students in STEM education," *Soc. Sci. Humanit. Open*, vol. 9, pp. 1–13, 2024. https://doi.org/10.1016/j.ssaho.2024.100839

[11] N. Pellas, I. Kazanidis, and G. Palaigeorgiou, "A systematic literature review of mixed reality environments in K-12 education," *Educ. Inf. Technol.*, vol. 25, pp. 2481–2520, 2020. https://doi.org/10.1007/s10639-019-10076-4

[12] F. Pallavicini and P. Anesa, "A narrative review on augmented reality in education," *Educ. Sci.*, vol. 16, no. 2, pp. 1–34, 2026. https://doi.org/10.3390/educsci16020261

[13] H. T. Crogman, V. D. Cano, E. Pacheco, R. B. Sonawane, and R. Boroon, "Virtual reality, augmented reality, and mixed reality in experiential learning: Transforming educational paradigms," *Educ. Sci.*, vol. 15, no. 3, pp. 1–23, 2025. https://doi.org/10.3390/educsci15030303

[14] M. A. Kuhail, A. Elsayary, S. Farooq, and A. Alghamdi, "Exploring immersive learning experiences: A survey," *Informatics*, vol. 9, p. 1032, 2022. https://doi.org/10.3390/informatics9040075

[15] R. Arifiani and I. Irwanto, "Augmented reality integrated with mobile learning in chemistry education: A bibliometric analysis from 2012–2022," *J. Educ. Online*, vol. 21, no. 2, pp. 1–7, 2024. https://doi.org/10.9743/JEO.2024.21.2.14

[16] V. Anesti and I. Irwanto, "Research on augmented reality in education: A bibliometric analysis," *J. Learn. Dev.*, vol. 12, no. 1, pp. 125–141, 2025. https://doi.org/10.56059/jl4d.v12i1.1314

[17] S. Angra, S. Jangra, Y. Gulzar, B. Sharma, G. Singh, and C. W. Onn, "Twenty-two years of advancements in augmented and virtual reality: A bibliometric and systematic review," *Front. Comput. Sci.*, vol. 7, pp. 1–10, 2025. https://doi.org/10.3389/fcomp.2025.1470038

[18] X. Guo, Y. Guo, and Y. Liu, "The development of extended reality in education: Inspiration from the research literature," *Sustainability*, vol. 13, no. 24, pp. 1–20, 2021. https://doi.org/10.3390/su132413776

[19] E. C. Magaña, A. C. Ariza, J. R. Palmero, and F. D. Guillén-Gámez, "Virtual, augmented, and mixed reality in the University environment: An analysis of scientific production," *J. New Approaches Educ. Res.*, vol. 14, pp. 1–20, 2025. https://doi.org/10.1007/s44322-025-00027-y

[20] K. E. Elfaki and E. M. Ahmed, "Digital technology adoption and globalization innovation implications on Asian Pacific green sustainable economic growth," *J. Open Innov. Technol. Mark. Complex.*, vol. 10, pp. 1–10, 2024. https://doi.org/10.1016/j.joitmc.2024.100221

[21] M. Jemala, "Long-term research on technology innovation in the form of new technology patents," *Int. J. Innov. Stud.*, vol. 5, no. 4, pp. 148–160, 2021. https://doi.org/10.1016/j.ijis.2021.09.002

[22] J. Loh, W. H. Chong, C. Lim-ratnam, M. Tan, and P. Ow, "Educational evaluation research in Asia: A scoping review," *Asia Pacific J. Educ.*, vol. 44, no. 3, pp. 552–568, 2024. https://doi.org/10.1080/02188791.2024.2390663

[23] T. Tene, J. Alexandra, M. Tixi, M. Salazar, C. V. Gomez, and S. Bellucci, "Integrating immersive technologies with STEM education: A systematic review," *Front. Educ.*, vol. 9, pp. 1–20, 2024. https://doi.org/10.3389/feduc.2024.1410163

[24] M. J. Maas and J. M. Hughes, "Virtual, augmented and mixed reality in K–12 education: A review of the literature," *Technol. Pedagog. Educ.*, vol. 29, no. 2, pp. 231–249, 2020. https://doi.org/10.1080/1475939X.2020.1737210

[25] O. Çavdar and B. Yıldırım, "Mixed, augmented and virtual reality in STEM education in the context of text mining: A bibliometric map analysis and systematic review," *Int. J. Curric. Instr.*, vol. 15, no. 3, pp. 2108–2131, 2023.

[26] K. Alhazzaa and W. Yan, "Bridging the gap between theory and practice: AR and VR for building thermal behavior in architectural education," *Energy Build.*, vol. 343, pp. 1–13, 2025. https://doi.org/10.1016/j.enbuild.2025.115940

[27] J. Y. Wong, A. B. Azam, Q. Cao, L. Huang, Y. Xie, and I. Winkler, "Evaluations of virtual and augmented reality technology-enhanced learning for higher education," *Electronics*, vol. 13, no. 8, pp. 1–16, 2024. https://doi.org/10.3390/electronics13081549

[28] C. Kefalis, C. Skordoulis, and A. Drigas, "Digital simulations in STEM education: Insights from recent empirical studies, a systematic review," *Encyclopedia*, vol. 5, no. 1, pp. 1–18, 2025. https://doi.org/10.3390/encyclopedia5010010

[29] J. C. Chen, H. C. Lin, K. Y. Lin, C. Y. Lin, and H. S. Hsiao, "Developing a hands-on activity using virtual reality to help students learn by doing," *J. Comput. Assist. Learn.*, vol. 36, no. 1, pp. 46–60, 2019. https://doi.org/10.1111/jcal.12389

[30] Y.-S. Chang, J.-Y. Kao, and Y.-Y. Wang, "Influences of virtual reality on design creativity and design thinking," *Think. Ski. Creat.*, vol. 46, p. 101127, 2022. https://doi.org/10.1016/j.tsc.2022.101127

[31] T. Huang, C. Chen, and C. Tseng, "Exploring learning effectiveness of integrating mixed reality in educational settings: A systematic review and meta-analysis," *Comput. Educ.*, vol. 234, pp. 1–25, 2025. https://doi.org/10.1016/j.compedu.2025.105327

[32] M. A. Alnuaimi and M. A. Awad, "VR environment support for STEM students – A case study," *Interact. Learn. Environ.*, vol. 34, no. 3, pp. 1647–1665, 2025. https://doi.org/10.1080/10494820.2025.2527168

[33] H.-C. Hung, M.-Y. Chuang, and C.-H. Chen, "Development and evaluation of collaboration scripts for long-distance VR team collaboration and co-creation in elementary STEM learning," *Int. J. Sci. Math. Educ.*, vol. 22, no. 1, pp. 59–80, 2024. https://doi.org/10.1007/s10763-024-10470-6

[34] Z. Jin, Y. Bai, W. Song, Q. Yu, X. Yue, and X. Jia, "DVRT: Design and evaluation of a virtual reality drone programming teaching system," *Comput. Graph.*, vol. 125, pp. 1–17, 2024. https://doi.org/10.1016/j.cag.2024.104114

[35] I. Irwanto, S. E. Sinarintyas, U. Cahyana, and G. A. B. Widana, "Using immersive virtual reality to enhance students' design thinking disposition and academic achievement," *Cogent Educ.*, vol. 13, no. 1, pp. 1–18, 2026. https://doi.org/10.1080/2331186X.2026.2616848

[36] M. A. AlGerafi, Y. Zhou, M. Oubibi, and T. T. Wijaya, "Unlocking the potential: A comprehensive evaluation of augmented reality and virtual reality in education," *Electronics*, vol. 12, no. 18, pp. 1–29, 2022. https://doi.org/10.3390/electronics12183953

[37] M. S. Dogru, F. Yüzbasioglu, and I. Arpaci, "A bibliometric trend analysis of augmented reality in STEM education," *Innov. Educ. Teach. Int.*, vol. 62, no. 6, pp. 1933–1948, 2025. https://doi.org/10.1080/14703297.2025.2483387

[38] R. Hidayat and Y. Wardat, "A systematic review of augmented reality in science, technology, engineering and mathematics education," *Educ. Inf. Technol.*, vol. 29, no. 8, pp. 9257–9282, 2024. https://doi.org/10.1007/s10639-023-12157-x

[39] Y. Wen, "Augmented reality enhanced cognitive engagement: Designing classroom-based collaborative learning activities for young language learners," *Educ. Technol. Res. Dev.*, vol. 69, pp. 843–860, 2020. https://doi.org/10.1007/s11423-020-09893-z

[40] S. Syskowski, S. Wilfinger, and J. Huwer, "Impact and classification of augmented reality in science experiments in teaching—A review," *Educ. Sci.*, vol. 14, no. 7, pp. 1–20, 2024. https://doi.org/10.3390/educsci14070760

[41] M. Adnan, L. F. Md Ibharim, Y. S. Wong, I. Yee, and Sukirman, "Development and usability of a traditional game simulation module with augmented reality technology (AR-SiGaSTEM) in online learning to strengthen STEM skills among students," *LUMAT Int. J. Math, Sci. Technol. Educ.*, vol. 12, no. 4, pp. 1–18, 2025. https://doi.org/10.31129/LUMAT.12.4.2226

[42] B. Çeken and N. Taşkın, "Multimedia learning principles in different learning environments: A systematic review," *Smart Learn. Environ.*, vol. 9, pp. 1–22, 2022. https://doi.org/10.1186/s40561-022-00200-2

[43] M. Sırakaya and D. A. Sırakaya, "Augmented reality in STEM education: A systematic review," *Interact. Learn. Environ.*, vol. 30, no. 8, pp. 1556–1569, 2022. https://doi.org/10.1080/10494820.2020.1722713

[44] I. Lasica, M. Meletiou-mavrotheris, and K. Katzis, "Augmented reality in lower secondary education: A teacher professional development program in Cyprus and Greece," *Educ. Sci.*, vol. 10, no. 4, pp. 1–20, 2020. https://doi.org/10.3390/educsci10040121

[45] T. T. N. Anh, "Enhancing astronomy skills: The role of mobile augmented reality in Vietnamese middle schools," *Int. J. Interact. Mob. Technol.*, vol. 18, no. 22, pp. 174–189, 2024. https://doi.org/10.3991/ijim.v18i22.51997

[46] I. Irwanto, L. Zeral, and I. Saputra, "The effect of augmented reality game-based learning on students' critical thinking disposition and academic achievement," *J. Technol. Sci. Educ.*, vol. 16, no. 1, pp. 68–79, 2026. https://doi.org/10.3926/jotse.3607

[47] Y. Hsu, Y. Lin, and B. Yang, "Impact of augmented reality lessons on students' STEM interest," *Res. Pract. Technol. Enhanc. Learn.*, vol. 12, no. 2, pp. 1–14, 2017. https://doi.org/10.1186/s41039-016-0039-z

[48] P. Milgramt and F. Kishinott, "A taxonomy of mixed reality visual displays," *IEEE Trans. Inf. Syst.*, vol. 77, no. 12, pp. 1321–1329, 1994. [Online]. Available: https://cs.gmu.edu/~zduric/cs499/Readings/r76JBo-Milgram_IEICE_1994.pdf

[49] S. Pérez-Muñoz, R. Castaño Calle, P. T. Morales Campo, and A. Rodríguez-Cayetano, "A systematic review of the use and effect of virtual reality, augmented reality and mixed reality in physical education," *Information*, vol. 15, no. 9, pp. 1–13, 2024. https://doi.org/10.3390/info15090582

[50] S. Liu, P. Toreini, and A. Maedche, "Mixed reality learning systems with head-mounted displays in higher education: A systematic review," *Technol. Knowl. Learn.*, pp. 1–35, 2025. https://doi.org/10.1007/s10758-025-09912-z

[51] I. Irwanto and E. Hutahaean, "Two decades of STEM education studies in higher education: A bibliometric analysis," *J. Turkish Sci. Educ.*, vol. 22, no. 3, pp. 451–467, 2025. https://doi.org/10.36681/tused.2025.023

[52] K. Y. Lin, C. J. Ku, H. T. Wei, K. C. Yu, and P. J. Williams, "Processes, challenges, and teacher roles in developing and implementing collaborative STEM curricula: Case studies of two Taiwanese schools," *Int. J. STEM Educ.*, vol. 12, pp. 1–19, 2025. https://doi.org/10.1186/s40594-025-00545-3

[53] B. B. Lofgran, L. K. Smith, and E. F. Whiting, "Science self-efficacy and school transitions: Elementary school to middle school, middle school to high school," *Sch. Sci. Math.*, vol. 115, no. 7, pp. 366–376, 2015. https://doi.org/10.1111/ssm.12139

[54] A. M. Young *et al.*, "Motivational decline and recovery in higher education STEM courses," *Int. J. Sci. Educ.*, vol. 40, no. 9, pp. 1016–1033, 2018. https://doi.org/10.1080/09500693.2018.1460773

[55] N. Donthu, S. Kumar, D. Mukherjee, N. Pandey, and W. M. Lim, "How to conduct a bibliometric analysis: An overview and guidelines," *J. Bus. Res.*, vol. 133, pp. 285–296, 2021. https://doi.org/10.1016/j.jbusres.2021.04.070

[56] R. Pranckute, "Web of Science (WoS) and Scopus: The titans of bibliographic information in today's academic world," *Publications*, vol. 9, no. 1, pp. 1–59, 2021. https://doi.org/10.3390/publications9010012

[57] D. Moher, A. Liberati, J. Tetzlaff, D. G. Altman, and T. P. Group, "Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement," *PLoS Med.*, vol. 6, no. 7, pp. 1–6, 2009. https://doi.org/10.1371/journal.pmed.1000097

[58] M. Aria and C. Cuccurullo, "Bibliometrix: An R-tool for comprehensive science mapping analysis," *J. Informetr.*, vol. 11, no. 4, pp. 959–975, 2017. https://doi.org/10.1016/j.joi.2017.08.007

[59] N. J. van Eck and L. Waltman, "Software survey: VOSviewer, a computer program for bibliometric mapping," *Scientometrics*, vol. 84, no. 2, pp. 523–538, 2010. https://doi.org/10.1007/s11192-009-0146-3

[60] J. Wang, D. Guo, and M. Jou, "A study on the effects of model-based inquiry pedagogy on students' inquiry skills in a virtual physics lab," *Comput. Human Behav.*, vol. 49, pp. 658–669, 2015. https://doi.org/10.1016/j.chb.2015.01.043

[61] D. T. Nipo, J. Lily, S. Idris, S. Pinjaman, and I. Bujang, "The nexus between information and communication technology (ICT), electricity access, governance and human development: Evidence from Asia-Pacific countries," *Economies*, vol. 11, no. 2, pp. 1–10, 2023. https://doi.org/10.3390/economies11020049

[62] C. Aguayo, T. Cochrane, and V. Narayan, "Key themes in mobile learning: Prospects for learner-generated learning through AR and VR," *Australas. J. Educ. Technol.*, vol. 33, no. 6, pp. 27–40, 2017. https://doi.org/10.14742/ajet.3671

[63] C. Moro, Z. Stromberga, and A. Stirling, "Virtualisation devices for student learning: Comparison between desktop-based (Oculus Rift) and mobile-based (Gear VR) virtual reality in medical and health science education," *Australas. J. Educ. Technol.*, vol. 33, no. 6, pp. 1–10, 2017. https://doi.org/10.14742/ajet.3840

[64] G. M. Masilo, S. Simelane-Mnisi, A. Mji, and I. Mokgobu, "Students' behavioural intention and challenges to bring your own device (BYOD) in higher education during COVID-19 and beyond," *World Trans. Eng. Technol. Educ.*, vol. 19, no. 1, pp. 10–15, 2021. https://doi.org/10.21125/edulearn.2020.1958

[65] A. D. Samala, S. Papadakis, and S. Rawas, "Global insights into mobile learning in higher education: A PRISMA-guided bibliometric analysis from 2007 to 2023," *Int. J. Educ. Reform*, pp. 1–31, 2025. https://doi.org/10.1177/10567879251341869

[66] D. W. Aksnes, L. Langfeldt, and P. Wouters, "Citations, citation indicators, and research quality: An overview of basic concepts and theories," *SAGE Open*, vol. 9, no. 1, pp. 1–17, 2019. https://doi.org/10.1177/2158244019829575

[67] J. Wang, R. Frietsch, and R. Hooi, "International collaboration leading to high citations: Global impact or home country effect?" *J. Informetr.*, vol. 18, no. 4, pp. 1–12, 2024. https://doi.org/10.1016/j.joi.2024.101565

[68] A. Gómez-espés, M. Färber, and A. Jatowt, "Benefits of international collaboration in computer science: A case study of China, the European Union, and the United States," *Scientometrics*, vol. 129, no. 2, pp. 1155–1171, 2024. https://doi.org/10.1007/s11192-023-04902-3

[69] J. C. Wang, C. Hsieh, T. Tsai, and S. Chung, "Utilization of government grants for funding: Insights into STEM education teachers in Taiwan," *Cogent Educ.*, vol. 12, no. 1, pp. 1–38, 2025. https://doi.org/10.1080/2331186X.2025.2530904

[70] Y. Peng, F. Zhao, and Y. Zheng, "Promoting equitable and high-quality STEM education in China from an ecological perspective," *Discip. Interdiscip. Sci. Educ. Res.*, vol. 7, pp. 1–10, 2025. https://doi.org/10.1186/s43031-025-00127-x

[71] P. Dorta-González and M. I. Dorta-González, "Citation differences across research funding and access modalities," *J. Acad. Librariansh.*, vol. 49, no. 4, pp. 1–20, 2023. https://doi.org/10.1016/j.acalib.2023.102734

[72] NTU, "NIE sets up a STEM Education Research Centre," 2018. https://www.ntu.edu.sg/nie/news-events/news/detail/nie-sets-up-a-stem-education-research-centre [Accessed: Feb. 12, 2026].

[73] Ministry of Science Technology and Innovation, "Future of STEM talent in Malaysia: A delphi approach," 2025. [Online]. Available: https://mastic.mosti.gov.my/storage/2026/01/Appendices-STI-Foresight-Report-2025-2040-Future-of-STEM-Talent-in-Malaysia-A-Delphi-Approach.pdf

[74] R. Schmidt and B. Stumpe, "Systematic review of mobile augmented reality applications in geography education," *Rev. Educ.*, vol. 13, no. 1, pp. 1–44, 2025. https://doi.org/10.1002/rev3.70042

[75] A. J. Lotka, "The frequency distribution of scientific productivity," *J. Washingt. Acad. Sci.*, vol. 16, no. 12, pp. 317–323, 1926.

[76] J. E. Hirsch, "An index to quantify an individual's scientific research output," *Proc. Natl. Acad. Sci. U. S. A.*, vol. 102, no. 46, pp. 16569–16572, 2005. https://doi.org/10.1073/pnas.0507655102

[77] H. Piwowar *et al.*, "The state of OA: A large-scale analysis of the prevalence and impact of open access articles," *PeerJ*, vol. 6, pp. 1–23, 2018. https://doi.org/10.7717/peerj.4375

[78] S. C. Bradford, "Sources of information on scientific subjects," *Engineering*, vol. 137, pp. 85–86, 1934.

[79] M. Mendoza, "Differences in citation patterns across areas, article types and age groups of researchers," *Publications*, vol. 9, pp. 1–23, 2021. https://doi.org/10.3390/publications9040047

[80] R. Miranda and E. Garcia-Carpintero, "Overcitation and overrepresentation of review papers in the most cited papers," *J. Informetr.*, vol. 12, no. 4, pp. 1015–1030, 2018. https://doi.org/10.1016/j.joi.2018.08.006

[81] X. Chen, D. Zou, H. Xie, and F. L. Wang, "Metaverse in education: Contributors, cooperations, and research themes," *IEEE Trans. Learn. Technol.*, vol. 16, no. 6, pp. 1111–1129, 2023. https://doi.org/10.1109/TLT.2023.3277952

[82] G. D. Boztaş, M. Berigel, F. Altınay, and Z. Altınay, "Learning modalities shaped by digital transformation in distance education: A bibliometric analysis of trends and reflections (2017–2023)," *Open Prax.*, vol. 17, no. 2, pp. 349–362, 2025. https://doi.org/10.55982/openpraxis.17.2.837

[83] F. Mufit, W. S. Dewi, S. Riyasni, and M. Dhanil, "Augmented reality with a cognitive conflict model and STEM integration on Newton's universal law of gravitation: Does practicing practical learning support scientific literacy?" *Int. J. Inf. Educ. Technol.*, vol. 15, no. 2, pp. 255–271, 2025. https://doi.org/10.18178/ijiet.2025.15.2.2239

[84] S. Rehman, R. Khatoon, and I. A. Khan, "Unlocking the potential of AI-enhanced mixed reality: Enhancing technical English proficiency for engineering students in the Gulf Region," *Arab World English J.*, vol. 16, no. 4, pp. 185–195, 2025. https://doi.org/10.24093/awej/vol16no4.10

[85] K. Ragab, E. Martínez-Jiménez, and E. Fernandez-Ahumada, "Students' perceptions of using interactive technology in developing their competencies in STEM classes in an applied technology school in the UAE," *J. Inf. Technol. Educ. Res.*, vol. 24, pp. 1–30, 2025. https://doi.org/10.28945/5631

[86] H. H. Mira, R. Chaker, I. Maria, and H. Nady, "Review of research on the outcomes of embodied and collaborative learning in STEM in higher education with immersive technologies," *J. Comput. High. Educ.*, vol. 37, pp. 1161–1198, 2025. https://doi.org/10.1007/s12528-024-09418-0

[87] I. Irwanto, T. Lintangnicita, U. Cahyana, and J. Cha, "Examining the effect of immersive virtual reality on 11th-grade students' creative thinking disposition and academic achievement," *Discov. Educ.*, vol. 4, pp. 1–16, 2025. https://doi.org/10.1007/s44217-025-00880-1

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