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Research Hotspots and Thematic Evolution in Technology Acceptance for Immersive Mathematics: A Bibliometric Visualization

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The integration of immersive technologies in mathematics education presents significant potential for enhancing learning experiences, yet its successful implementation hinges on user acceptance, a domain predominantly explained by the Technology Acceptance Model (TAM). However, the rapid proliferation of research has resulted in a fragmented literature, lacking comprehensive synthesis of its intellectual structure and evolution. This study addresses this gap through bibliometric analysis of 425 Scopus publications (2021-2025) using R Bibliometrix and Biblioshiny. Findings reveal: (1) Intellectual Structure - exponential growth (31.13% annually) with distinct geographical patterns showing Asian productivity leadership versus European citation impact; (2) Conceptual Structure, a fundamental schism between technological clusters (AR/VR) and pedagogical streams, with AI emerging as a bridging theme; (3) Social Structure, moderate international collaboration (24.94%) with limited South-South cooperation; (4) Thematic Evolution, progression from pandemic-responsive research toward AI and Mixed Reality as emerging frontiers. Notably, Mixed Reality remains significantly underexplored compared to AR/VR dominance. The study identifies three critical research trajectories: developing MR-specific TAM extensions, creating integrated technological-pedagogical frameworks, and establishing diversified global research networks. This research provides scholars with a definitive state-of-the-art reference, offers educators evidence-based implementation insights, and guides developers in creating user-centered immersive learning applications,

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ultimately facilitating more effective adoption of immersive technologies in mathematics education. Overall, these findings underscore that advancing the field requires bridging the persistent gap between technological innovation and pedagogical practice to ensure meaningful, scalable, and sustainable integration of immersive technologies in mathematics learning.

Introduction

The contemporary educational landscape is undergoing a profound transformation, driven by the integration of digital technologies to enhance pedagogical efficacy and student engagement. This shift is particularly salient within Science, Technology, Engineering, and Mathematics (STEM) education, where innovative tools are being leveraged to demystify complex abstract concepts (English, 2023; Smith et al., 2022; Tan et al., 2023). Mathematics education, a critical pillar of STEM, perennially grapples with significant challenges, including student anxiety (Cuder et al., 2024) and difficulties in fostering spatial reasoning (Zhu et al., 2023). In response to these challenges, immersive technologies categorized under the umbrella of Extended Reality (XR), including Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), have emerged as a disruptive force (Murala & Panda, 2023). These technologies promise to reconfigure learning environments into interactive, spatially aware spaces where mathematical abstractions can be visualized, manipulated, and intuitively understood, thereby potentially revolutionizing pedagogical approaches.

A growing corpus of empirical and review-based research substantiates this transformative potential, demonstrating significant pedagogical benefits. These include enhanced mastery of abstract concepts (Campos et al., 2022; Holly et al., 2021; Lindner et al., 2022), increased self-efficacy and engagement, particularly in project-based and maker contexts (Chiang & Liu, 2023; Hobbs & Holley, 2022; Shu & Huang, 2021). Further empirical studies confirm that interactivity in AR systems optimizes learning outcomes (Yi-Ming Kao & Ruan, 2022), while applied research shows the successful optimization of MR for technical education (Wu et al., 2021). At the review level, syntheses by Pellas et al. (2020), Velázquez & Méndez, (2021), and Yegorina et al. (2021) consolidate evidence on spatial and motivational learning, while Palacios et al. (2022) and Marrero-Galván & Hernández-Padrón (2022) expand the scope by addrcessing methodological gaps and advocating for interdisciplinary insights and promising school-based AR pilots (McNerney et al., 2023). Collectively, this body of work underscores the breadth of impact; however, it also reveals a critically fragmented landscape and a predominant focus on VR and AR, leaving the distinct affordances of true Mixed Reality for visualizing and manipulating complex mathematical constructs largely unexplored.

Despite the considerable promise held by immersive technologies and the growing investment in their development, their successful adoption and sustained implementation within mathematics education are not assured. The pedagogical value of any educational technology is ultimately mediated by its acceptance and utilization by its end-users, educators and students (Dimitrijević & Devedžić, 2021). The Technology Acceptance Model (TAM), since its inception by Davis (1989), has provided the predominant theoretical framework for explaining and predicting user adoption of information systems, centering on core constructs such as Perceived Usefulness (PU) and Perceived Ease of Use (PEOU). Its extensions have further refined its explanatory power (Venkatesh & Davis, 2000). Consequently, a substantial and rapidly expanding corpus of literature has sought to apply TAM to understand the adoption dynamics of XR in mathematics learning. However, the very proliferation of these studies has led to a fragmented and complex body of knowledge, making it increasingly difficult to discern the field's overarching intellectual structure, conceptual interrelations, and evolutionary trajectory.

A preliminary bibliometric mapping of this domain reveals a critical nuance that further sharpens the focus of this investigation. The intellectual landscape is currently dominated by research on AR and VR, while the specific concept of MR has yet to crystallize as a dominant thematic cluster. This indicates that the distinct adoption dynamics of true MR environments, which enable real-time interaction between digital and physical objects, represent a significant and underexplored frontier. Concurrently, the TAM functions not as a transient 'hotspot' but as a foundational 'Basic Theme,' confirming its role as the field's mature theoretical bedrock. This configuration presents a pivotal opportunity: to apply this robust theoretical framework to the next generation of immersive technology, MR, which remains conspicuously under-studied through the lens of acceptance models.

To address these identified gaps, this study employs a rigorous bibliometric analysis to systematically map and visualize the scholarly discourse concerning TAM within immersive mathematics education. Bibliometrics offers a powerful, quantitative paradigm for analyzing the meta-characteristics of a large publication corpus, enabling the objective identification of intellectual patterns and trends (Hoang, 2025). This study is guided by the following research questions (RQs):

(1) What is the intellectual structure of the field, as revealed through the analysis of influential authors, journals, countries, and highly cited documents?
(2) What is the conceptual structure of the research domain, and what are the predominant thematic clusters and research hotspots identified through keyword co-occurrence analysis?
(3) What is the social structure of the field, characterized by collaboration networks among authors and countries?
(4) How have the research themes evolved temporally, and what are the potential future research trajectories?

Theoritical Background

Technology Acceptance Model (TAM): Evolution and Applicability

The TAM, introduced by Davis (1989), remains the most influential framework for understanding user adoption of information systems. Its foundational premise is that two primary cognitive beliefs determine an individual's intention to use a technology: Perceived Usefulness (PU), the degree to which a person believes a system will enhance their performance, and Perceived Ease of Use (PEOU), the degree to which using a system is perceived to be free from effort. These beliefs directly influence attitude toward use, behavioral intention, and ultimately, actual system use.

The model's robustness has been confirmed through its application across diverse domains, including e-learning and educational technology (Granić & Marangunić, 2019). However, its parsimony also led to critiques regarding its potential oversimplification of social and contextual factors. This spurred the development of key extensions:

TAM2 incorporated social influence processes (Subjective Norm) and cognitive instrumental processes (Job Relevance, Output Quality) (Venkatesh & Davis, 2000).

(1) TAM3 further integrated the determinants of PEOU and PU, providing a more comprehensive nomological network (Venkatesh & Bala, 2008).

(2) The Unified Theory of Acceptance and Use of Technology (UTAUT) consolidated elements from eight models, introducing constructs like social influence, facilitating conditions, and hedonic motivation, with moderating effects of age, gender, and experience (Venkatesh et al., 2003).

For the context of immersive learning technologies, these extended models are particularly relevant. The adoption of such complex tools by students and teachers is not merely a function of utility and ease but is also shaped by social pressures (e.g., institutional mandates, peer influence), facilitating conditions (e.g., access to hardware, technical support), and the intrinsic enjoyment or hedonic motivation derived from the immersive experience itself.

In addition to these model extensions, a more granular examination of TAM constructs is essential for understanding their applicability to immersive learning technologies. PU and PEOU consistently emerge as the strongest predictors of BI, yet empirical studies in XR-enhanced learning environments reveal the importance of additional psychological and experiential variables. Presence and Immersion, for instance, have been shown to elevate PU by deepening learners' cognitive engagement and enhancing perceived instructional value, while Interactivity directly contributes to PEOU by reducing operational complexity during virtual object manipulation. Hedonic Motivation, central in UTAUT, also plays a critical role in XR adoption, as the enjoyment derived from immersive environments strengthens user intention to engage with the technology. Facilitating Conditions and Social Influence further shape adoption through institutional support and peer dynamics. Together, these constructs form an interconnected network that is particularly relevant for understanding acceptance within complex, multisensory environments such as AR, VR, and MR.

Immersive Learning Technologies

The technological domain of this study is encapsulated by the term XR, a continuum ranging from the completely real to the fully virtual environment (Stanney et al., 2021). This spectrum is operationalized through three primary technologies:

- VR creates a completely computer-simulated environment, occluding the physical world to induce a sense of immersion and presence. In education, VR is often leveraged for simulations and exploratory learning in risk-free environments.
- AR superimposes digital information (e.g., images, 3D models, annotations) onto the user's view of the real world, typically via smartphones or tablets. It enhances the physical environment with contextual, interactive data.
- MR represents a more advanced point on the spectrum where digital and physical objects co-exist and interact in real-time. Unlike AR's simple overlay, MR allows users to manipulate and interact with virtual objects as if they were physically present, often through see-through headsets.

A critical factor differentiating these technologies is the psychological state of "Presence" (or telepresence), the subjective experience of "being there" in a mediated environment (Tjostheim & Waterworth, 2022). The level of presence induced by a technology is a key determinant of its pedagogical impact and user experience, and it is intricately linked to TAM constructs, as a stronger sense of presence can enhance perceived usefulness and enjoyment.

The Pedagogical Imperative for Immersive Mathematics Education

The convergence of TAM and XR finds a compelling use-case in mathematics education, a discipline plagued by challenges of abstraction, student anxiety, and low engagement. Immersive technologies offer unique pedagogical affordances that directly address these issues:

- Visualizing the Abstract: Complex mathematical concepts from geometry, calculus, and algebra can be transformed from abstract symbols into tangible, manipulable 3D objects. This enables students to develop spatial reasoning and an intuitive understanding of functions, graphs, and geometric transformations.
- Enhancing Engagement and Motivation: The interactive and often game-like nature of XR environments can significantly increase intrinsic motivation and engagement, a factor closely aligned with the "Hedonic Motivation" construct in UTAUT.
- Providing Situated Learning: AR and MR, in particular, allow for learning within a physical context, making mathematics relevant to the student's immediate environment. This situatedness can strengthen the perceived relevance and, consequently, the perceived usefulness of the learning tool.

Therefore, investigating the acceptance of XR through the TAM lens is not merely an academic exercise; it is a critical inquiry into the factors that will determine whether these powerful pedagogical tools can transition from technological novelties to effectively integrated components of the mathematics curriculum.

Despite the increasing research attention devoted to XR in education, several critical gaps remain unaddressed. First, while AR and VR dominate empirical studies, MR is substantially underrepresented despite its distinct affordances that differ conceptually and functionally from traditional AR overlays. Second, existing acceptance studies tend to focus on isolated variables or small-scale empirical findings, with limited attempts to synthesize the broader intellectual, conceptual, and social evolution of the field. Third, prior literature rarely integrates technological determinants (e.g., presence, interactivity) with pedagogical dimensions relevant to mathematics learning, resulting in fragmented theoretical development. These gaps underscore the need for a comprehensive bibliometric mapping that consolidates the existing evidence base, clarifies the position of MR within the XR landscape, and identifies emerging research trajectories for technology acceptance in immersive mathematics education.

Methodology

This study employed a systematic bibliometric analysis to map the intellectual structure and thematic evolution of research on the TAM in immersive mathematics education. The methodology was designed to ensure reproducibility and rigor, adhering to the principles of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Moher et al., 2009) and leveraging the computational power of the Bibliometrix R-package and its Biblioshiny web interface (Aria & Cuccurullo, 2017).

Data Source and Search Strategy

The Scopus database was selected as the sole source for data retrieval due to its extensive and high-quality curation of peer-reviewed literature across the relevant disciplines of social sciences, computer science, and education, which aligns precisely with the interdisciplinary nature of this study. A comprehensive and iterative search strategy was developed to construct a representative corpus of the target literature.

In addition to its disciplinary coverage, the exclusive use of Scopus is methodologically justified by its highly standardized metadata format, which is fully compatible with the analytical requirements of the Bibliometrix R-package and Biblioshiny. As these tools require a single, consistently structured dataset to ensure accurate performance, science mapping, and network analyses, combining multiple databases (e.g., Web of Science, ERIC) would introduce metadata heterogeneity that can compromise analytical reliability. Therefore, Scopus was selected as the most appropriate and technically consistent source for this study's bibliometric workflow, while recognizing that multi-database approaches may be considered in future investigations.

The primary search query was executed to capture the intersection of four core conceptual domains: the theoretical framework (TAM), the technological context (Mixed Reality), the application domain (Education), and the specific subject area (Mathematics Learning). The final query, refined through multiple pilot searches to balance sensitivity and specificity, was structured as follows:

> (ALL ("technology acceptance model") AND ALL (education) AND ALL ("mathematics learning") AND ALL ("mixed reality")) AND PUBYEAR > 2020 AND PUBYEAR < 2026 AND (LIMIT-TO (DOCTYPE , "ar"))

This query was designed to search for the terms across title, abstract, and keywords, ensuring a comprehensive initial capture. The publication year filter was set to focus on the contemporary landscape from 2021 onwards, including early-access articles, and the document type was restricted to articles to prioritize original research. This initial search, conducted on September 25, 2025, returned 1,612 documents.

Data Screening and Eligibility: A PRISMA-Guided

To refine the initial dataset into a focused and relevant corpus for bibliometric synthesis, a systematic screening process was implemented, following the transparent workflow outlined in the PRISMA statement (Moher et al., 2009). The process, illustrated in Figure 1, involved two critical stages of screening applied to the 1,612 identified records.

The first stage involved a rigorous title and abstract screening against explicit inclusion criteria: (1) the study must empirically investigate or significantly discuss the TAM (or its extensions); (2) the technological context must involve an immersive technology (VR, AR, or MR); and (3) the application must be squarely within mathematics education. This screening resulted in the exclusion of 1,187 records. The vast majority of these exclusions were due to a misalignment in scope; for instance, papers discussed TAM in general e-learning, immersive technologies in non-mathematical contexts, or mathematics education without a focus on technology acceptance.

This stringent process yielded 425 articles for the final bibliometric synthesis. A subsequent full-text eligibility check confirmed that these 425 articles all met the inclusion criteria, as the prior screening had been highly effective. Therefore, no further documents were excluded at this stage, resulting in a final corpus of 425 articles deemed highly relevant for analysis. The PRISMA chart is depicted in Figure 1.

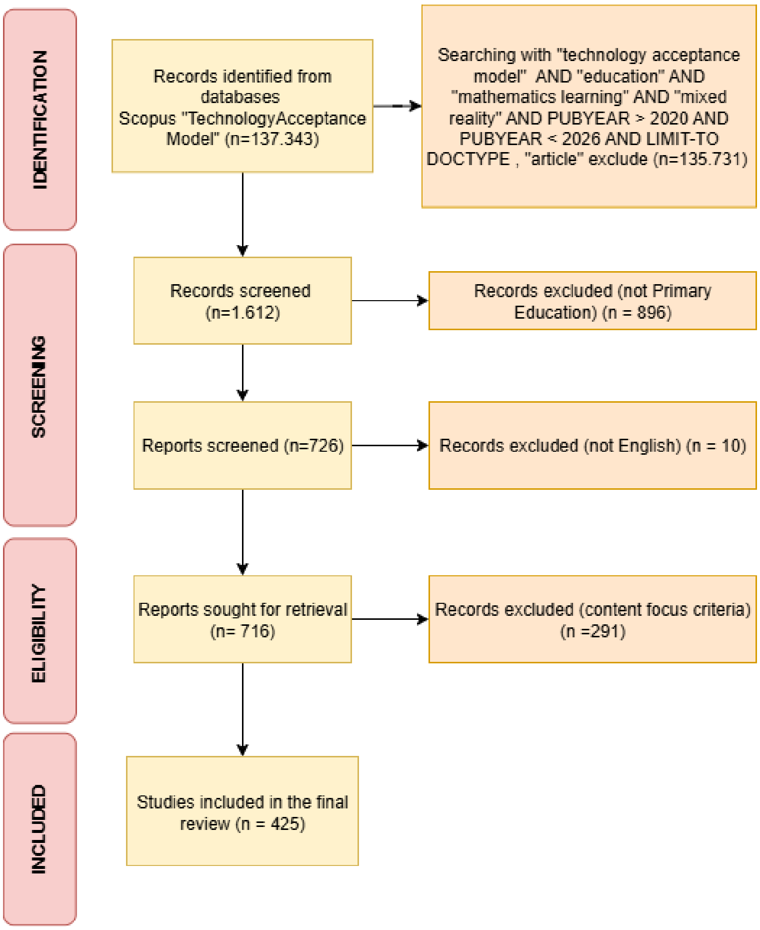


Figure 1. The PRISMA flow diagram

Data Analysis and Analytical Framework

The final corpus of 425 articles was analyzed using the R-based Bibliometrix package and its Biblioshiny web interface, employing a comprehensive bibliometric triangulation approach. The analytical framework was specifically designed to address each research question through validated techniques and visualizations displayed in Table 1.

Table 1. Analytical framework mapping research questions to bibliometric techniques

Research Question (RQ)	Specific Biblioshiny Analysis / Visualization	Purpose in Addressing the RQ
RQ1: Intellectual Structure	Annual Scientific Production	To establish the temporal growth trajectory and research intensity of the field.
	Bradford's Law	To identify the core journals that are most central to the field's discourse.
	Most Relevant Sources & Source Production Over Time	To list key publishing venues and track their evolving contribution.
	Lotka's Law	To quantify author productivity patterns and identify the proportion of core vs. transient contributors.
	Most Relevant Authors & Author Production Over Time	To pinpoint the leading researchers and their productivity trends.
	Country Production & Corresponding Author's Country	To map the geographical distribution of research output.
	Most Global Cited Documents	To identify the seminal, high-impact publications that form the field's knowledge base.
	Most Cited Countries	To reveal which countries produce the most influential research.
RQ2: Conceptual Structure	Thematic Map	To identify and classify the main research themes into developmental quadrants (Motor, Niche, Emerging, Basic).
	WordCloud & Most Relevant Words	To provide a visual representation of conceptual densities and the most frequently used keywords.
	Factorial Map	To illustrate the conceptual structure and relationships among keywords or documents in a two-dimensional space
RQ3: Social Structure	Country Collaboration Map	To visualize international research partnerships and collaboration networks between countries.
	Network of Authors	To reveal co-authorship patterns and identify distinct research communities.
	Three-Field Plot	To illustrate the complex relationships between countries, keywords, and sources.
RQ4: Thematic Evolution	Source Production Over Time	To contextualize thematic shifts by showing which journals drive new trends and how the publishing landscape evolves.
	Trend Topics	To track the rise and fall of specific keywords over time, identifying emerging and declining research fronts.
	Thematic Map	To document the progression, merger, or dissolution of major thematic clusters across different time slices.

Result

The bibliometric analysis encompasses a final corpus of 425 articles published between 2021 and 2025, derived from 176 distinct sources. The descriptive metrics, summarized in Table 2, reveal a field characterized by dynamic growth and collaborative research practices.

Table 2. Main Information

Description	Results
Timespan	2021:2025
Sources	176
Documents	425
Annual Growth Rate	31.13%
Document Average Age	1.41 years
Average Citations per Doc	11.34
Authors	1324
International Co-authorships %	24.94%
Co-Authors per Doc	3.52

The bibliometric profile reveals a field in a phase of robust and accelerated expansion, as evidenced by a remarkable 31.13% annual growth rate and the recency of the corpus, with an average document age of just 1.41 years. This dynamism is coupled with significant and immediate scholarly impact, where the substantial average of 11.34 citations per document indicates rapid knowledge absorption despite the literature's novelty. The intellectual structure is fundamentally collaborative and globalized, characterized by large research teams (3.52 co-authors per document) and a considerable degree of international cooperation (24.94%). Furthermore, the dissemination of knowledge across 176 distinct sources points to a diverse and interdisciplinary publication landscape, suggesting the field's relevance spans computer science, education, and psychology, yet also hints at a lack of consolidation around a few core journals at this stage of its development.

RQ1: What is the intellectual structure of the field, as revealed through the analysis of influential authors, journals, countries, and highly cited documents?

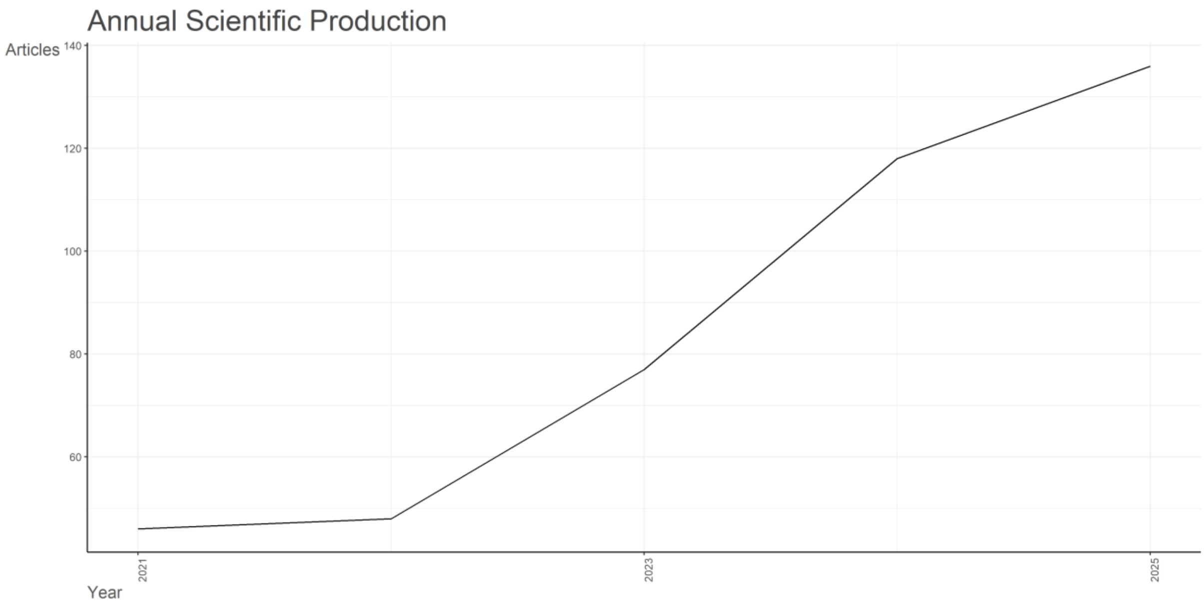
In mapping the intellectual structure of the field, descriptive indicators such as temporal growth, country ecosystems, and author productivity were not treated merely as frequency counts but as structural signals that reveal how research communities consolidate, how scholarly influence is distributed, and how the field progresses toward maturity. When interpreted relationally, these indicators function as proxies for identifying scientific concentration, collaboration intensity, and the emergence of foundational research fronts. Accordingly, the intellectual structure is not reflected simply in the upward trajectory of publication counts, but in the underlying patterns that illuminate how scholarly influence, research consolidation, and disciplinary leadership have evolved. The identification of core journals, the concentration of contributions from a small set of prolific authors, and the production impact asymmetry between Asian and European research ecosystems collectively demonstrates the formation of knowledge hubs and the crystallization of foundational intellectual anchors within this emerging domain.

The intellectual structure of TAM research in immersive mathematics education reveals a field in a phase of exponential expansion and global consolidation. Annual scientific production has surged from 46 articles in 2021 to 136 in 2025, reflecting a compound annual growth rate exceeding 30%. This remarkable growth is channeled through a well-defined core of academic sources, with Bradford's Law confirming Education and Information Technologies as the dominant journal, accounting for over 12% of all publications and establishing a primary conduit for knowledge dissemination in this domain.

Table 3. Core Performance Indicators and Intellectual Structure

Indicator	Top Elements	Metric	Intellectual Significance
Productivity & Growth	2021 (46) → 2025 (136)	425 total documents	Field exhibits exponential growth phase (CAGR >30%)
Core Sources (Bradford)	Educ. Inf. Technol. (52) Interact. Learn. Environ. (15) J. Comput. Assist. Learn. (15)	Zone 1: 10 journals	Concentrated knowledge dissemination through technology education venues
Author Productivity (Lotka)	1,210 single-publication authors (91.4%) Andić B & Lavicza Z (8 each)	α = 1.663	Highly collaborative field with concentrated expertise
Geographical Production	China, Indonesia, Turkey, Malaysia, USA	20+ countries	Asian dominance in research output
Scholarly Impact	Germany (27.4 avg citations) Greece (25.8) China (12.8)	TC = 1318 (China)	European leadership in research influence
Foundational Works	Adarkwah (2021) - 249 citations Backfisch (2021) - 146 citations Lampropoulos (2024) - 119 citations	Norm. TC = 16.72	Seminal papers focus on on

Geographically, the field exhibits a distinct production-impact dichotomy. Analysis of country production and corresponding authors reveals Asian dominance in research output, led by China, Indonesia, and Malaysia. However, European nations demonstrate superior scholarly influence, with Germany (27.4 average citations per article) and Greece (25.8) emerging as quality leaders despite lower production volumes. This pattern suggests different national research strategies, with some regions focusing on quantity and others on impact.



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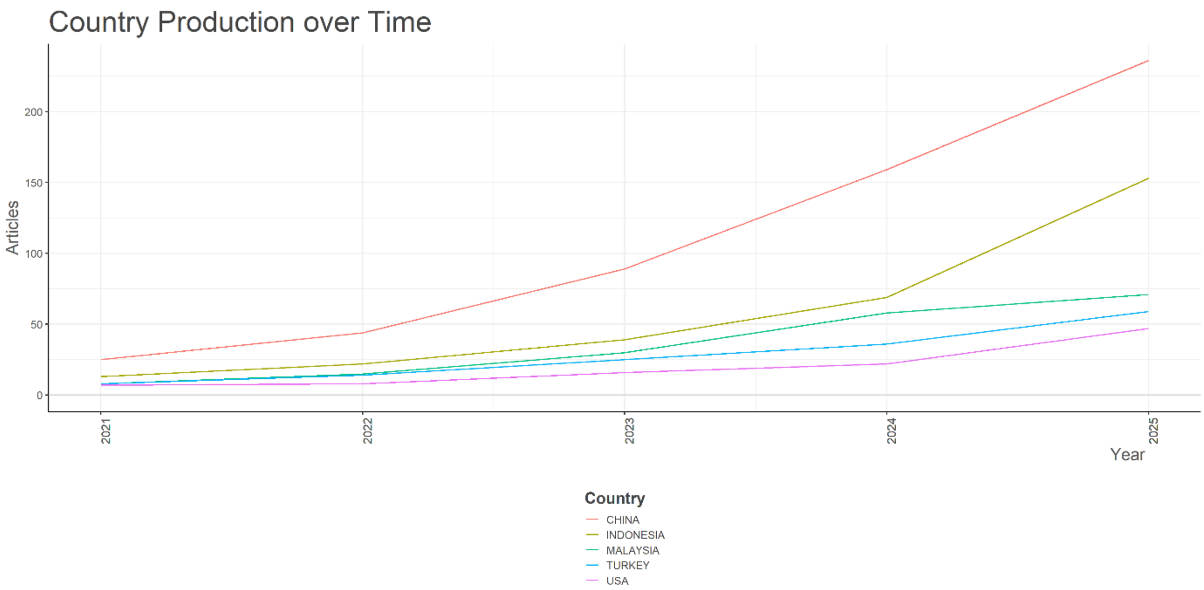

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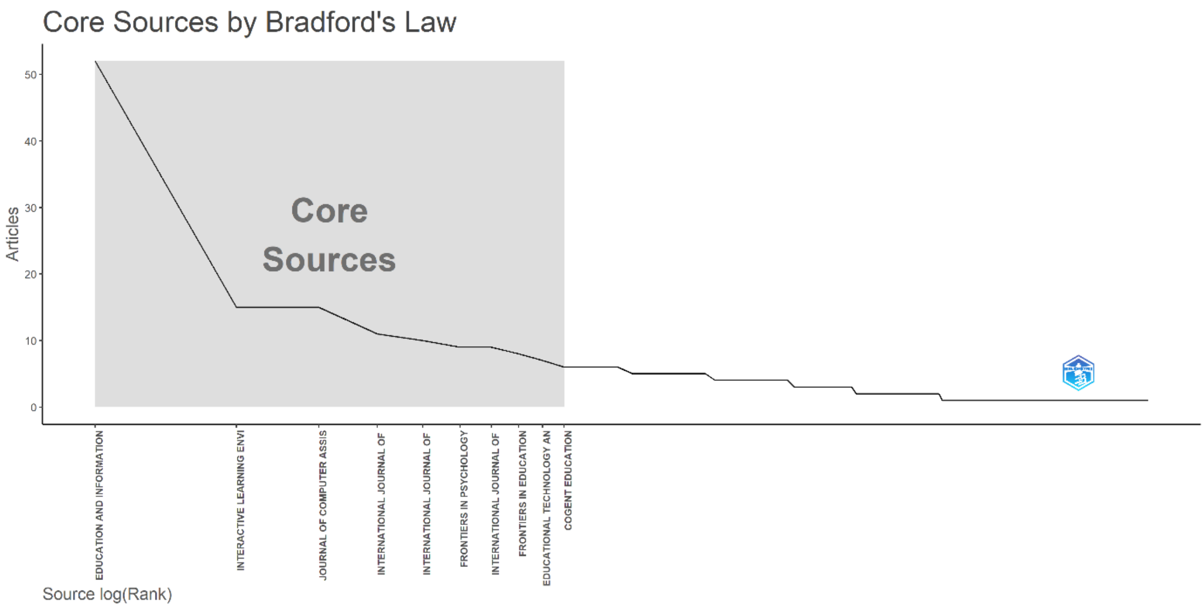

(2c)

Figure 2. (2a) Annual Scientific Production, (2b) Country Production Over Timer, and (2c) Bradford's Law

The intellectual foundations are shaped by a concentrated yet collaborative author network. Lotka's Law distribution shows 91.4% of authors contribute single publications, while a small core of prolific researchers notably Andić B and Lavicza Z, drives sustained scholarly discourse. The most globally cited documents, led by Adarkwah (2021) with 249 citations, establish the theoretical groundwork in online learning acceptance, while Lampropoulos's (2024) rapidly influential work signals the field's pivot toward augmented reality applications.

RQ2: What is the conceptual structure of the research domain, and what are the predominant thematic clusters and research hotspots identified through keyword co-occurrence analysis?

The conceptual architecture of TAM research in immersive mathematics education reveals a field characterized by clear thematic stratification and distinct intellectual clusters. Through a triangulation of factorial analysis and thematic mapping, this section delineates the field's conceptual foundations and their strategic positioning.

Table 4. Conceptual Structure

Analytical Dimension	Keywords	Strategic Interpretation
Dominant Research Foci	• Augmented Reality (63) • Virtual Reality (36) • Artificial Intelligence (24) • Technology Acceptance Model (13)	AR/VR dominate as the established technological core, while AI represents a significant emerging interest, signaling the field's expansion beyond traditional immersive technologies.
Conceptual Clusters (Factorial Analysis)	• Technology Cluster: AR, VR, Mathematics, Metaverse • Pedagogy Cluster: Teacher Education, Professional Development • Learning Sciences Cluster: Collaborative Learning, Motivation	Reveals a fundamental conceptual dichotomy between technological innovation and pedagogical application, indicating parallel research streams that require greater integration. The separation highlights a critical gap where technological potential and classroom adoption are studied in isolation.
Thematic Strategic Positioning	• Motor Themes: AR, VR (High Density & Centrality) • Emerging Themes: AI, Metaverse (Rising Density) • Basic Themes: Education, TAM (High Centrality) • Niche Themes: 3D Modeling, Gamification	Establishes AR/VR as the mature, driving force of the field while identifying AI and the Metaverse as the new, rapidly developing frontier. The persistent centrality of TAM underscores its role as the field's foundational theoretical framework, even as applications evolve.

The factorial analysis (Figure 3) reveals a fundamental conceptual dichotomy between technology-driven research streams (augmented reality, virtual reality, mathematics) and pedagogy-focused investigations (teacher education, professional development). This structural separation suggests parallel development paths that have yet to achieve full integration, presenting a significant opportunity for future research that bridges technological innovation with pedagogical adoption models.

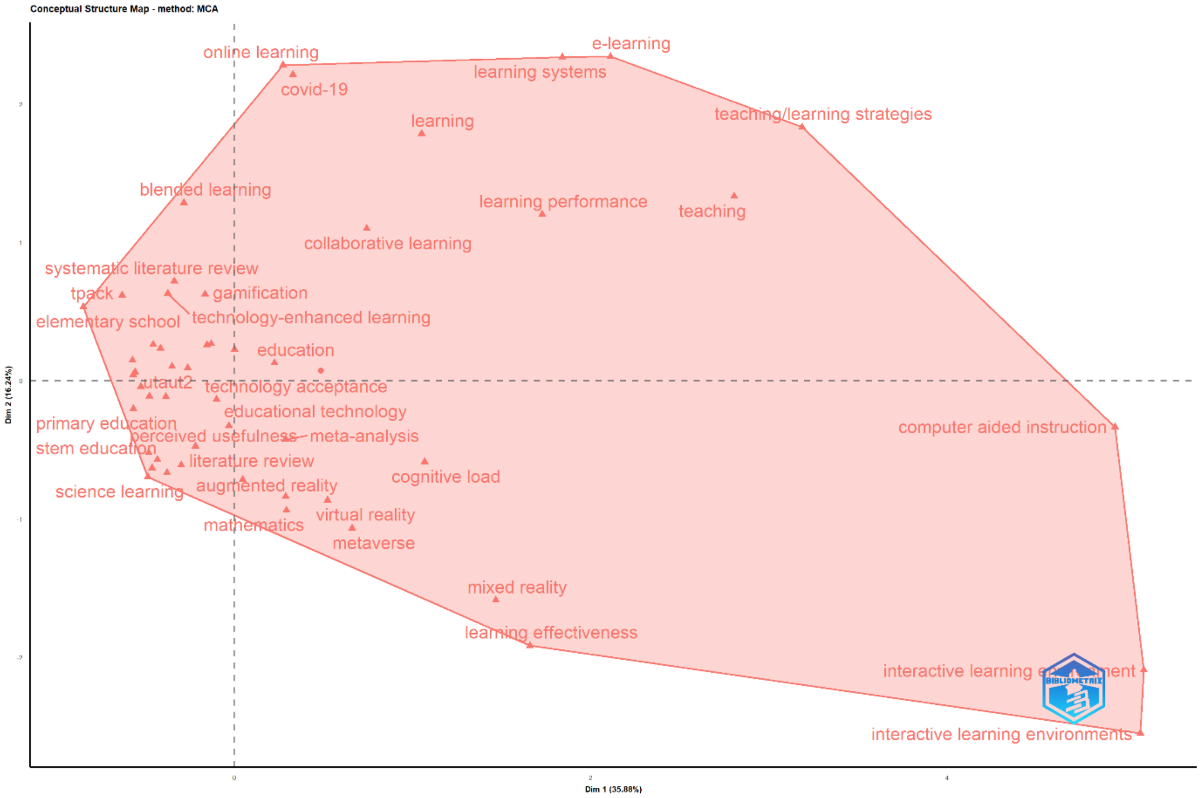

Figure 3. Conceptual Structure Map - Factorial Analysis

The strategic positioning of research themes becomes evident through the thematic map analysis (Figure 4), where augmented and virtual reality emerge as well-developed motor themes central to the field's identity. Concurrently, artificial intelligence positions as a strong emerging theme, demonstrating high development (density) but not yet the same level of integration (centrality) as the established motor themes. This configuration indicates a field with a solid core identity while actively expanding its research frontiers.

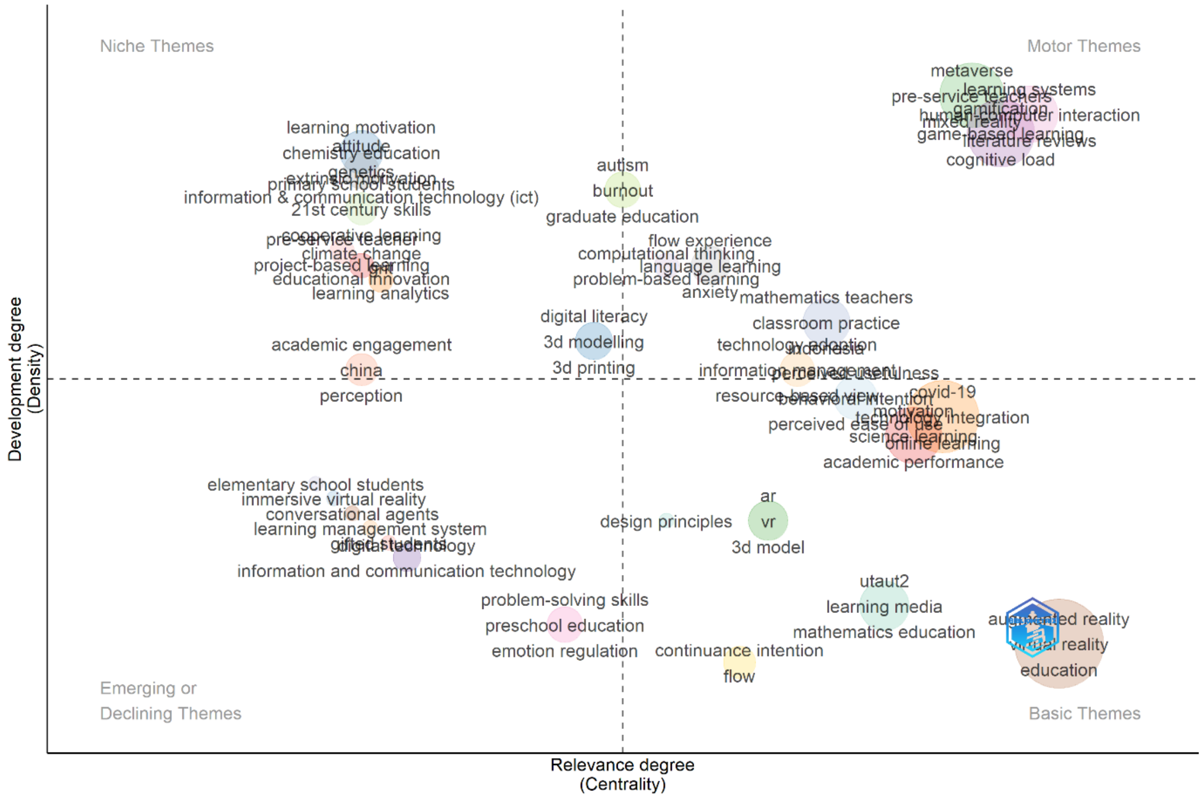

Figure 4. Thematic Map

The word cloud visualization (Figure 5) provides immediate visual confirmation of the field's conceptual priorities, emphasizing the overwhelming dominance of augmented reality while clearly signaling the arrival of artificial intelligence as a substantial research interest.

Figure 5. Word Cloud

This comprehensive conceptual analysis demonstrates a field in active transition, maintaining its core focus on immersive technology acceptance while rapidly incorporating artificial intelligence and next generation learning environments. The identified thematic structure provides both a map of current research concentrations and a trajectory for future scholarly investigation.

RQ3: What is the social structure of the field, characterized by collaboration networks among authors and countries?

Analysis of the social structure reveals a field characterized by moderate globalization with distinct collaborative hubs and emerging regional networks. The collaboration patterns demonstrate both international integration and persistent geographical clustering, providing insights into the field's knowledge production dynamics as presented in Table 5.

Table 5. Social Structure and Collaboration Patterns

Analytical Level	Key Findings	Network Interpretation
International Collaboration	• 24.94% International Co-authorship • Strong EU-Asia partnerships (Austria-China-Germany) • Emerging ASEAN collaborations (Indonesia-Malaysia-Thailand)	The moderate international co-authorship rate indicates a transitioning field moving toward globalization, yet significant collaboration barriers persist. The robust Austria-China-Germany triangle represents the primary knowledge exchange channel between European pedagogical expertise and Asian technological innovation, while emerging ASEAN networks signal regional consolidation in educational applications.
Author Collaboration Clusters	• Primary Cluster: Anđić B, Lavicza Z, Weinhandl R (3D printing/STEM) • Secondary Cluster: Hwang G, Chen S, Yu Z (AR/game-based learning) • Tertiary Cluster: Wijaya TT, Songkram N (microgame adoption)	The field is structured around three distinct research schools with high internal cohesion but limited cross-cluster collaboration. This pattern reveals deep thematic specialization where each cluster operates as an independent innovation ecosystem. The minimal integration between clusters, particularly between technological development (Cluster 1-2) and pedagogical application (Cluster 3), represents a significant opportunity for interdisciplinary synthesis.
Geographical-Thematic Links	• China: AI, Virtual Reality, STEM • Austria/Germany: 3D modeling, teacher education • Indonesia/Thailand: Mobile learning, mathematics education • Turkey: Educational technology, technology integration	Clear regional research specializations emerge, reflecting complementary expertise distribution and resource allocation patterns. Asian countries demonstrate leadership in technological innovation (China's AI/VR focus), while European nations excel in pedagogical integration and teacher development. Southeast Asian researchers concentrate on contextual applications in mathematics education, creating both efficient specialization and potential knowledge silos that require strategic bridging initiatives.
Corresponding Author Distribution	• China (28.7%) • Indonesia (15.2%) • Turkey (9.4%) • USA (7.1%) • Germany (5.9%)	The corresponding author distribution indicates Asian leadership in research initiative and project coordination, with China and Indonesia collectively accounting for 43.9% of research leadership. This contrasts with the citation impact patterns observed in RQ1, where European nations achieved higher average citations per publication, suggesting a complementary relationship where Asian coordination combines with European impact to drive the field forward.

The country collaboration map (Figure 6) illustrates a polycentric network structure with several influential hubs. The Austria-China-Germany collaboration represents the most substantial transnational partnership, facilitating knowledge exchange between European pedagogical expertise and Asian technological innovation. Simultaneously, emerging ASEAN networks centered around Indonesia, Malaysia, and Thailand demonstrate regional consolidation in mathematics education applications, though with weaker connections to global research streams.

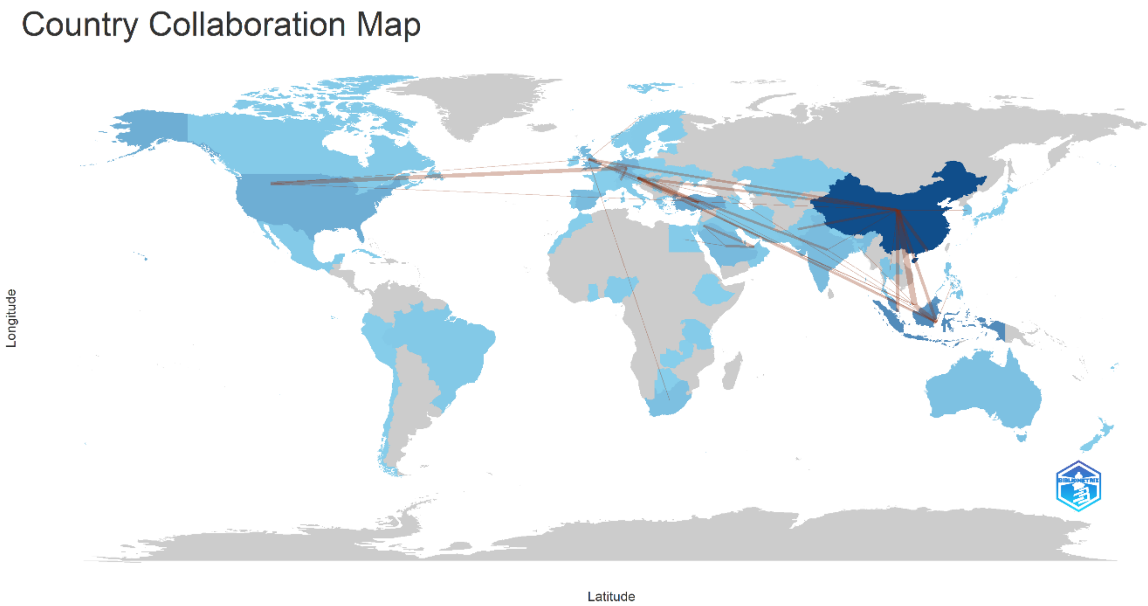

Figure 6. Country Collaboration Map

At the micro-level, author collaboration networks (Figure 7) reveal three distinct research schools with high internal cohesion but limited interconnection. The dominant Anđić-Lavicza cluster exhibits the strongest collaboration density, focusing on 3D modeling and printing applications. The secondary Hwang-Chen and tertiary Wijaya-Songkram clusters demonstrate parallel development in augmented reality and mobile learning respectively, suggesting opportunities for cross-fertilization between these technologically adjacent but socially separated research streams.

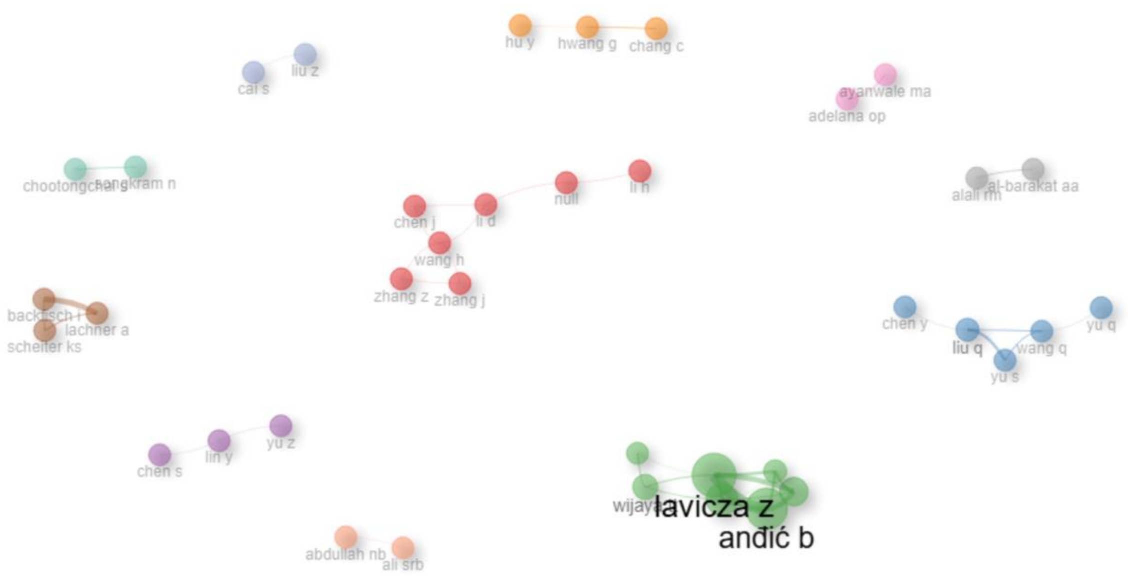

Figure 7. Author Collaboration Network

The three-field plot (Figure 8) elucidates the knowledge flow patterns between geographical origins, research contributors, and thematic domains. Chinese authorship strongly associates with artificial intelligence and virtual reality applications, while European researchers dominate 3D modeling and teacher education studies. Southeast Asian scholars show concentration in mathematics education and mobile learning, reflecting both regional priorities and potentially constrained resource allocations.

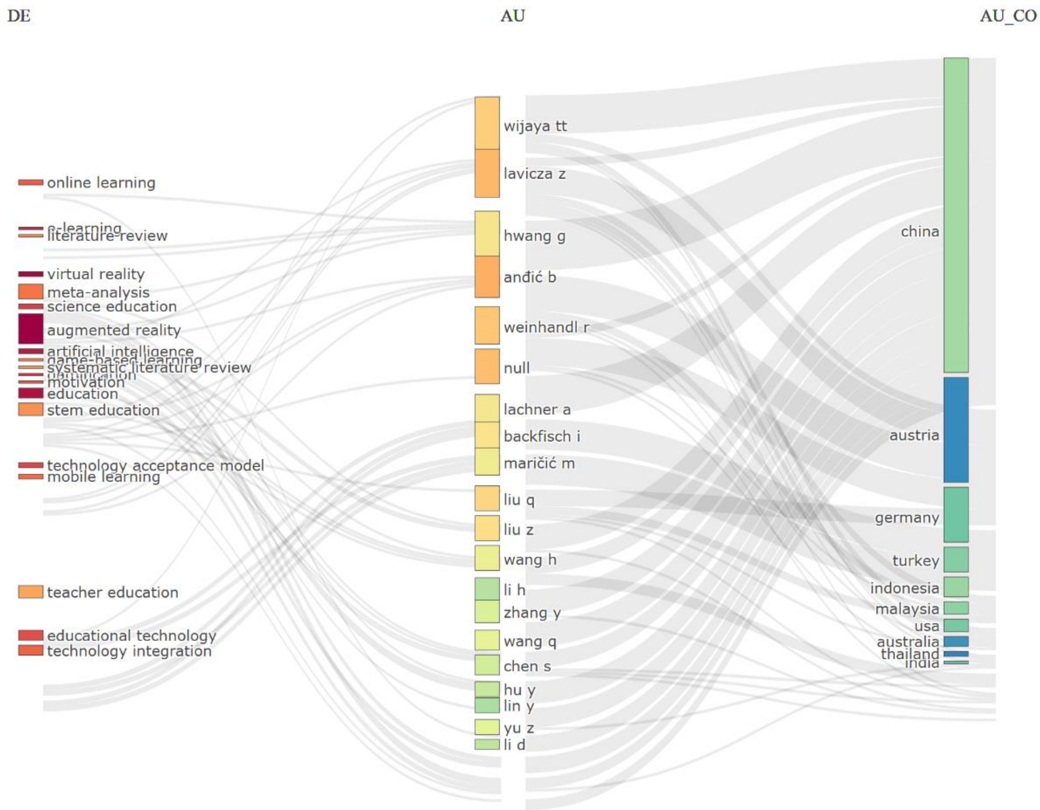

Figure 8. Three-Field Plot: Keyword-Author-Country

In summary, the social structure of TAM research in immersive mathematics education displays moderate internationalization with clear regional specializations. While established EU-Asia partnerships drive knowledge production, the limited South-South collaboration and segregated research clusters suggest significant potential for enhanced integration through targeted networking initiatives and interdisciplinary research programs.

RQ4: How have the research themes evolved temporally, and what are the potential future research trajectories?

The intellectual landscape of TAM research in immersive mathematics education has undergone significant transformation between 2021 and 2025, evolving from a pandemic-reactive field into one focused on sophisticated technology integration. The analysis reveals clear temporal patterns and emerging trajectories that define the field's future direction as presented in Table 6.

Table 6. Thematic Evolution and Future Research Trajectories

Analytical Dimension	Key Findings	Strategic Interpretation
Temporal Evolution Patterns	• Declining Themes: Covid-19, E-learning (2021-2022 peak) • Stable Themes: TAM, Interactive Learning (consistent presence) • Exponential Themes: AI, Gamification, Digital Literacy (sharp growth from 2023)	Confirms the field's maturation beyond reactive pandemic studies toward proactive exploration of engaging and intelligent learning environments. The persistent relevance of TAM underscores its enduring role as the core theoretical framework.
Institutional Production Trends	• Asian Leadership: Beijing Normal University (17 pubs, 2025) • European Excellence: Johannes Kepler University (14 pubs, 2025) • Indonesian Growth: Multiple universities showing 3-5x increase	Reveals a shifting geographical center of gravity, with Asian institutions demonstrating remarkable growth rates and European universities maintaining strong, consistent output, shaping a polycentric global knowledge network.
Thematic Trajectories & Future Pathways	• Consolidation: AR/VR themes merging with AI concepts • Divergence: Specialized niches forming around gamification and digital literacy • Pedagogical Shift: Growing focus on pre-service teacher preparation	Suggests that future research will likely involve AI-enhanced immersive experiences, requiring investigation of new pedagogical models and acceptance factors for these complex, integrated technologies.

The analysis of trend topics (Figure 9) reveals a clear chronological progression in research focus. Early terms like "e-learning" and "Covid-19" show peak relevance during 2021-2022, representing the field's reactive phase to global educational disruptions. From 2023 onward, the focus shifts decisively toward core immersive technologies, with "augmented reality" and "virtual reality" establishing sustained dominance. The most recent phase (2024-2025) marks the emergence of "artificial intelligence," "gamification," and "digital literacy" as the new frontiers, indicating the field's progression toward more intelligent, engaging, and critically aware technology integration.

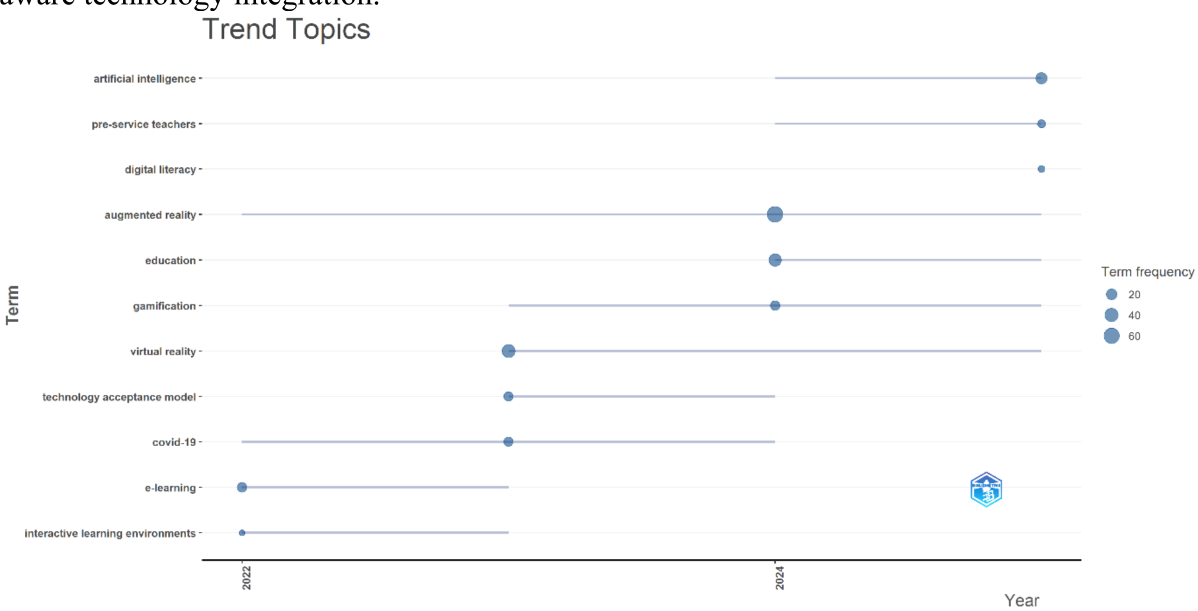

Figure 9. Trend Topics Evolution (2021-2025)

Institutional production patterns provide crucial context for these thematic shifts. As shown in Figure 10, leading institutions demonstrate remarkable growth trajectories that align with the field's thematic evolution. Beijing Normal University's dramatic increase from 0 publications in 2021 to 17 in 2025 exemplifies the Asian research surge in advanced technologies. Similarly, Indonesian universities collectively show a 3-5 fold increase in output, particularly in digital literacy and gamification applications. European institutions like Johannes Kepler University maintain strong, steady growth, focusing on the pedagogical integration of these technologies.

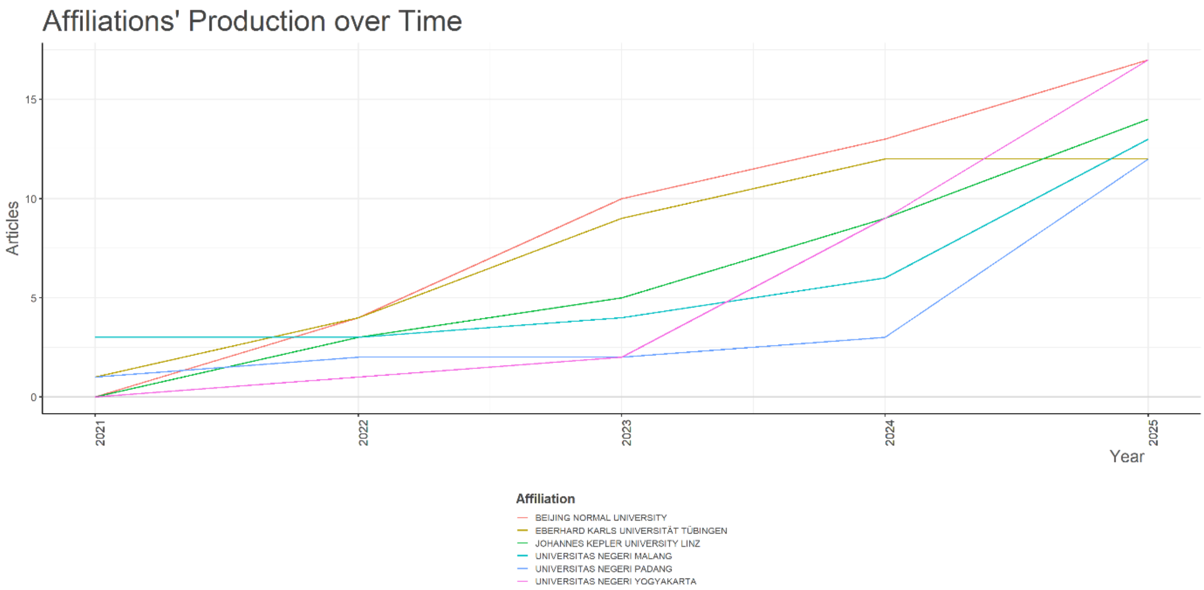

Figure 10. Institutional Production Over Time

The thematic evolution analysis suggests three primary future research trajectories. First, the technical integration trajectory will likely explore AI-driven personalization within AR/VR environments, requiring new TAM extensions to account for intelligent system adoption. Second, the pedagogical adaptation trajectory demands investigation of how pre-service teachers develop competencies for these complex technological ecosystems. Finally, the critical digital literacy trajectory emerges from the convergence of gamification and digital literacy, pointing toward the need for critical engagement frameworks in immersive mathematics education. This comprehensive evolutionary analysis demonstrates a field in dynamic transition, having established a solid foundation in immersive technology acceptance while rapidly advancing toward AI-enhanced, pedagogically-sound, and critically-engaged learning environments. The identified trajectories provide a strategic roadmap for future scholarly investigation in this rapidly evolving domain.

Discussion

This study aimed to map the intellectual, conceptual, and social structures of TAM research in immersive mathematics education, with particular attention to the evolving roles of AR, VR, and MR. Before engaging in detailed interpretation, it is important to clarify what the findings reveal about the developmental trajectory of this research domain. Bibliometric mapping, when employed not merely as a descriptive tool but as a relational analytical framework, makes it possible to uncover structural patterns that indicate how research communities consolidate, how influence circulates, and how emerging technologies become embedded (or fail to become embedded) within educational discourse.

While publication counts, author distributions, or country outputs alone may offer limited insight, their integration with core bibliometric indicators such as Bradford's Law, Lotka's Law, thematic clustering, and conceptual co-occurrence patterns provides a macro-structural understanding of how the field is evolving. This methodological positioning is particularly essential for emerging technologies, where consolidation, fragmentation, and the formation of conceptual anchors cannot be fully captured through narrative review alone. In this sense, the bibliometric approach used in this study offers a necessary vantage point for understanding how immersive technologies and TAM-related constructs gain momentum, stabilize, or diverge over time.

The findings of this study resonate strongly with the broader landscape of educational technology research, situating the evolution of TAM within a well-defined context. The temporal progression from pandemic-centric "e-learning" terminology toward specialized foci on "augmented reality" and a steeply rising "artificial intelligence" trajectory from 2023 onward reflects a field maturing beyond emergency remote teaching. This aligns with global bibliometric trends, where metaverse research has experienced rapid growth, particularly in 2023-2024, with China, the United States, and South Korea demonstrating leading citation impact (Sontay & Karamustafaoğlu, 2025). This trajectory suggests that immersive technology research is not expanding arbitrarily but is becoming increasingly specialized and theoretically refined, mirroring global technological shifts. This parallel development underscores the global momentum behind immersive technologies and validates the observed evolutionary pattern within the specialized domain of mathematics education.

Empirical evidence substantiates the pedagogical value driving this technological shift. A consolidating body of research demonstrates that VR and AR significantly enhance student engagement, comprehension, and collaborative learning (Tene et al., 2024; Wu et al., 2021). These benefits are operationalized in specific classroom interventions; for instance, NeoTrie VR has been shown to enrich geometry instruction through collaborative manipulation (Rodríguez et al., 2021), while AR-based game applications effectively improve mathematical competence in primary education (Ahmad & Junaini, 2022). The cleARmaths application further exemplifies this potential by providing intuitive visualization for vector geometry, receiving positive reception despite facing technological barriers to widespread adoption (Schutera et al., 2021). The efficacy of these tools is reinforced by meta-analytic findings confirming that VR has a significant positive effect on student learning across grade levels, with fully immersive interventions yielding the greatest gains (Villena-Taranilla et al., 2022).

However, the conceptual structure analysis reveals a critical fragmentation between technological and pedagogical research streams, indicating parallel yet disconnected development paths. This schism manifests in real-world pedagogical practices, where a disconnect persists between advanced technological potential and classroom implementation. Elmalı et al. (2025) illustrate this gap, finding that early childhood mathematics instruction in Türkiye remains predominantly teacher-centered and narrowly focused on number concepts, highlighting an urgent need for the diverse, child-centered approaches that immersive technologies could enable. This underscores the necessity of aligning technological integration with pedagogical objectives that foster reflective thinking, problem-solving, and deeper conceptual understanding (Kuncoro et al., 2025), suggesting that future TAM research must expand beyond mere technology adoption to encompass these critical cognitive outcomes.

A paramount finding of this analysis is the identified research frontier concerning MR. The conceptual mapping reveals a conspicuous underrepresentation of MR terminology compared to established AR/VR research, a gap previously signaled by Kuhail et al. (2022). This is a significant omission, as emerging evidence indicates MR's considerable promise; Almufarreh (2023) demonstrated that MR can significantly enhance academic performance and satisfaction through experiential learning. The convergence of MR with AI presents a further transformative pathway. AI applications in primary mathematics are recognized for fostering dynamic, adaptive learning environments that support Sustainable Development Goals (Topkaya et al., 2025), while advanced metaverse frameworks point to new frontiers for blending real and digital spaces (Bandyopadhyay et al., 2023). The application of TAM within these emerging, AI-enhanced MR environments thus presents a critical challenge and opportunity for theoretical advancement.

The social network and intellectual structure analyses further reveal operational challenges that impede field cohesion. The observed suboptimal international collaboration rate (24.94%), characterized by limited South-South cooperation, restricts the diversity of perspectives and limits investigation into cultural dimensions of technology acceptance. This is problematic, as studies like Kusherbaevna et al. (2025) reveal significant gender differences in attitudes toward VR, underscoring the need for inclusive, context-specific models advocated by Tene et al. (2024). Furthermore, resistance to adoption persists due to cost, technical barriers, and pedagogical uncertainty, even among stakeholders who recognize the technology's value (Schnyder et al., 2025). This highlights that teacher readiness and professional development, particularly in under-researched settings, are crucial for successful implementation (Shaw et al., 2021).

Although this study offers a comprehensive macro-level mapping, it does not examine the substantive content of individual publications, nor how immersive technologies are conceptually or pedagogically enacted within specific learning contexts. A complementary qualitative or content-focused analysis, such as examining the theoretical framing, learning designs, or empirical outcomes used across the included studies, would enrich understanding of how AR, VR, and MR are being operationalized. Future research can build upon the present bibliometric insights by integrating qualitative synthesis to provide a deeper account of how theoretical models, design principles, and classroom applications converge within immersive mathematics education.

Synthesizing these insights, three critical research trajectories emerge. First, investigating MR-specific acceptance factors, such as spatial presence, gesture-based interactions, and the manipulation of physical-digital objects, constitutes an urgent empirical direction. Second, developing integrated theoretical frameworks that explicitly connect technological affordances with pedagogical practices is essential to bridge the identified conceptual divide. Third, examining cultural dimensions of technology acceptance through expanded and diversified global collaborations is necessary to address geographical imbalances and incorporate diverse perspectives, ultimately fostering more equitable implementation.

This analysis demonstrates that while the adoption of AR and VR in mathematics education has grown steadily, its impact remains contingent on overcoming significant conceptual and operational hurdles (Buentello-Montoya et al., 2021). The promise of tools like AR for improving knowledge acquisition and motivation is clear (Zapata et al., 2024), and shared VR environments show great potential for collaborative knowledge construction through multimodal interactions (Huang et al., 2023). By prioritizing the investigation of MR, developing integrated pedagogical-technological frameworks, and fostering inclusive global research networks, the field can advance from validating basic technology adoption toward a nuanced understanding of complex human-technology interactions, thereby fully realizing the transformative potential of immersive technologies in mathematics education.

Conclusion

This study provides a structured bibliometric mapping of TAM research in immersive mathematics education, clarifying how the field has evolved intellectually, conceptually, and socially. Rather than reiterating descriptive patterns, the analysis highlights deeper structural dynamics, including the dominance of AR and VR over the still-emerging MR, the rise of artificial intelligence as a thematic connector, and the persistent misalignment between technological innovation and pedagogical application. These patterns indicate a field that is expanding rapidly but remains unevenly developed, with theoretical consolidation and pedagogical integration progressing at different rates.

The findings also illuminate what bibliometric analysis can and cannot reveal about emerging technologies. While structural indicators help identify influential knowledge hubs, research frontiers, and global collaboration ecosystems, they do not capture how immersive technologies are conceptually framed, implemented in classrooms, or theorized within mathematics learning. Advancing the field therefore, requires complementary research approaches. Future studies should undertake qualitative and content-focused analyses to examine MR-specific factors such as spatial presence, gesture-based interaction, and cognitive demands, while also developing integrated theoretical models that link technological affordances to pedagogical goals. Strengthening global research networks, particularly by expanding South–South and cross-cultural collaborations, is equally essential to broaden the applicability and inclusivity of TAM-related insights.

This study acknowledges the limitation of relying solely on Scopus, which, although methodologically consistent for Bibliometrix workflows, may not capture scholarship indexed in Web of Science, ERIC, or regional databases. Future research should therefore consider multi-database triangulation to enhance comprehensiveness and generalizability. Despite this constraint, the present mapping offers a consolidated reference point for understanding the structural development of TAM research in immersive mathematics education and provides a roadmap for advancing methodological diversification, theoretical depth, and pedagogically grounded innovation in this rapidly evolving domain.

Declarations

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Conflict of Interest: The author declares no conflict of interest.
Informed Consent: Not applicable, as the study did not involve human participants.
Data availability: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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