

# Augmented Reality and Artificial Intelligence in Education: Mapping Intelligent Learning Ecosystems through Bibliometric and BERTopic Analysis

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## Abstract

This study presents a hybrid bibliometric and BERTopic-based synthesis of a decade of rapid growth in research on the convergence of augmented reality (AR) and artificial intelligence (AI) in education. Drawing on publications retrieved from Web of Science and Scopus between 2014 and 2024, the study combines bibliometric analysis with transformer-based semantic topic modelling to examine the evolution, intellectual structure, and thematic development of AR-AI educational research. An initial dataset of 2,634 records, comprising 648 from Web of Science and 1,986 from Scopus, was refined through deduplication, relevance screening, and manual validation, resulting in a master corpus of 2,159 records. From this corpus, 1,709 records were analysed using Bibliometrix to examine publication growth, geographic distribution, sources, authorship, collaboration patterns, citations, and keywords. A separate semantic corpus of 1,848 documents was used for BERTopic modelling after text-quality filtering and peripheral-topic removal. The BERTopic model identified 16 meaningful topics with a low outlier rate of 5.57%, which were synthesised into five higher-level themes: healthcare and clinical simulation; intelligent and adaptive learning systems; professional and high-risk training; human-centred, assistive, and inclusive learning; and metaverse, cultural, and emerging learning ecosystems. The findings indicate increasing convergence of AR and AI within domain-specific learning environments that combine immersive visualisation, learner modelling, adaptive feedback, simulation, and data-informed support. The study contributes a large-scale, dual-database, and semantically enriched synthesis that integrates structural mapping with conceptual interpretation. The results offer implications for designing inclusive, ethical, and pedagogically meaningful AR-AI learning environments.

**Keywords:** Artificial Intelligence, Augmented Reality, Technology-enhanced Learning, Immersive Learning, Bertopic, Bibliometric Analysis

## Introduction

Advances in Information and Communication Technology (ICT) have transformed education by expanding access to digital resources, enabling flexible modes of learning, and creating new opportunities for learner engagement (Global Education Monitoring Report, 2023; Zou et al., 2025). Despite these developments, persistent challenges remain in relation to learner engagement, personalisation, knowledge retention, accessibility, and educational equity. These challenges have increased interest in technologies capable of supporting more adaptive, immersive, responsive, and learner-centred educational experiences.

Among these technologies, Augmented Reality (AR) and Artificial Intelligence (AI) have become increasingly prominent in contemporary education. AR enhances learning by integrating digital information with physical environments, thereby supporting visualisation, contextual understanding, situated interaction, and experiential learning (Hakiki et al., 2022; Milgram et al., 1995; Rodriguez-Saavedra et al., 2025). AI, by contrast, contributes capabilities such as adaptive learning, intelligent tutoring, learning analytics, automated feedback, prediction, and personalised instructional support (Ikram et al., 2026; Létourneau et al., 2025). Although these technologies have often developed as distinct research streams, their increasing intersection is creating new possibilities for educational environments in which immersive interaction is combined with adaptive intelligence and data-informed support.

The convergence of AR and AI can therefore be understood as more than the parallel use of two educational technologies. AR provides spatial visualisation, contextual interaction, and immersive representation, while AI enables learner modelling, adaptation, intelligent feedback, automated decision support, and personalisation. When these capabilities are combined, they contribute to the development of intelligent learning ecosystems in which digital content, learner data, adaptive mechanisms, immersive interfaces, and pedagogical support interact within a connected educational environment. Such ecosystems are increasingly evident across formal education, healthcare and clinical training, professional development, industrial learning, and emerging virtual and mixed learning environments. Recent studies have also extended this convergence through the integration of AR with large language models and other AI-supported systems to provide personalised and scalable learning experiences in open and distance education (Lampropoulos, 2025; Oju et al., 2026). Collectively, these developments indicate that AR-AI convergence may support immersive visualisation, adaptive feedback, personalised learning pathways, simulation-based training, and more context-sensitive educational experiences (Lampropoulos, 2025; Tene et al., 2024). As these AR-AI-enabled ecosystems evolve, research attention has expanded beyond technological functionality to include pedagogical effectiveness, accessibility, responsible implementation, and sustainability. Questions concerning privacy, transparency, algorithmic bias, inclusion, equitable access, and the pedagogical appropriateness of automated support increasingly influence the design and adoption of intelligent educational systems (Khupe et al., 2026; Lampropoulos & Evangelidis, 2025; Sripan & Jeerapattanatorn, 2025). Understanding the development of AR and AI as converging rather than isolated educational technologies has consequently become important for identifying the conceptual structure, dominant applications, emerging directions, and unresolved challenges within the field.

Existing reviews have provided valuable insights into AR, AI, immersive technologies, and Education 4.0, including publication trends, technological applications, learning outcomes,

and pedagogical implications. However, much of this literature has examined AR and AI independently or has treated them as separate components within the broader educational technology landscape. Bibliometric studies have frequently emphasised publication output, citations, countries, authors, journals, and keyword co-occurrence, while systematic reviews have generally relied on smaller samples and manual thematic synthesis. These approaches are valuable, but they provide limited insight into how previously distinct AR- and AI-related research streams are increasingly intersecting to form a broader convergence around intelligent, adaptive, and immersive learning environments.

A further limitation concerns the analytical methods used to examine the conceptual organisation of rapidly expanding interdisciplinary literature. Traditional bibliometric indicators can reveal the structural characteristics of a field, but they do not necessarily capture latent semantic relationships across large collections of titles and abstracts. Similarly, conventional topic modelling approaches such as Latent Dirichlet Allocation (LDA), as well as manual coding, may have difficulty representing contextual relationships within interdisciplinary and conceptually heterogeneous corpora. Transformer-based topic modelling provides an opportunity to complement bibliometric analysis by identifying semantically related research clusters from document embeddings and thereby supporting a richer interpretation of the underlying knowledge structure.

Against this background, the present study focuses specifically on the convergence of AR and AI in education rather than treating all AR and AI research as equivalent or unrelated bodies of literature. The broader search and screening process captured studies addressing AR, AI, and their integration because the development of convergence cannot be understood solely from studies in which both technologies are already fully integrated. AR- or AI-focused studies were retained where they contributed directly to understanding the technological, pedagogical, conceptual, or application pathways through which AR-AI convergence has emerged. The analytical emphasis, however, is on identifying how these previously distinct research streams intersect and collectively contribute to the development of intelligent learning ecosystems.

Accordingly, this study examines AR-AI education research published between 2014 and 2024, a decade characterised by substantial growth in immersive, adaptive, and data-driven educational technologies. Records from Web of Science and Scopus are analysed using a hybrid methodological framework that combines bibliometric analysis with transformer-based BERTopic modelling. Bibliometrix is used to examine publication growth, citation patterns, collaboration networks, source dynamics, and other structural characteristics of the literature, while BERTopic is applied to titles, abstracts, and keywords to identify latent semantic topics and their relationships. A PRISMA-style workflow is used to support transparency and reproducibility throughout corpus construction, screening, and analysis.

The novelty of this study lies not simply in mapping publications associated with AR and AI, but in examining how these research streams are increasingly converging within education and how that convergence is reflected structurally and semantically across the literature. The study makes four contributions. First, it expands the evidence base through a dual-database approach that improves interdisciplinary coverage across Web of Science and Scopus. Second, it applies a transparent and reproducible process for corpus construction, screening,

and validation. Third, it integrates bibliometric mapping with transformer-based semantic topic modelling, enabling simultaneous examination of the field's structural and conceptual development. Fourth, it synthesises the identified topics into higher-level themes that explain how AR and AI are contributing to intelligent learning ecosystems across healthcare education, adaptive learning systems, professional and high-risk training, human-centred, assistive, and inclusive learning, and emerging immersive environments.

This study is guided by the following research questions:

- **RQ1:** What are the publication, citation, collaboration, and source trends in AR-AI education research from 2014 to 2024 across Web of Science and Scopus?
- **RQ2:** What semantic themes emerge from BERTopic modelling of AR-AI education literature?
- **RQ3:** How do these themes reveal the structure and evolution of intelligent learning ecosystems enabled by AR and AI?
- **RQ4:** What future research, practical, ethical, and policy directions emerge from the bibliometric and semantic synthesis?

### Related Work and Theoretical Background

Research on AR, AI, and immersive technologies in education has expanded substantially over the past decade. Bibliometric studies have documented sustained growth in AR-related educational research, while systematic and scoping reviews have reported increasing adoption of AI-enabled approaches such as intelligent tutoring systems, adaptive learning environments, learning analytics, automated feedback, and personalised instructional support (Anesti & Irwanto, 2025; Ikram et al., 2026; Singh et al., 2024). More recent studies have begun to examine the intersection of AI with AR, virtual reality (VR), and extended reality (XR), highlighting their potential to support learner engagement, personalisation, immersive interaction, and learning performance across diverse educational settings (Garg et al., 2025; Lampropoulos & Evangelidis, 2025; Yan et al., 2025).

However, the existing evidence base remains fragmented. Many reviews examine AR, AI, VR, or XR as separate technological domains, while others focus on specific application areas such as healthcare, STEM education, professional training, or higher education. Consequently, although previous studies provide valuable insights into individual technologies and their educational effects, they offer a less comprehensive account of how AR- and AI-related research streams are increasingly intersecting to form broader intelligent learning ecosystems. In addition, many reviews rely on relatively small corpora, manual synthesis, or conventional bibliometric indicators, which can limit understanding of the latent conceptual relationships underlying this interdisciplinary field.

The development of AR-AI-enabled learning environments can be understood through several complementary educational theories. Constructivist perspectives emphasise the active construction of knowledge through interaction, prior experience, and social engagement, while experiential learning highlights the role of concrete experience, reflection, conceptualisation, and active experimentation in learning (Kolb, 2014; Vygotsky, 1978). These perspectives are particularly relevant to AR because immersive and context-aware environments allow learners to interact with digital representations embedded within authentic or simulated settings. Situated learning similarly emphasises participation within

meaningful social and contextual environments, providing a theoretical basis for AR-supported learning activities embedded in real-world or practice-oriented contexts (Lave & Wenger, 1991).

Cognitive load theory and multimedia learning theory provide an additional foundation for understanding the design of immersive educational environments. While AR and related technologies can enrich representation and interaction, poorly designed immersive experiences may also increase extraneous cognitive demands. Effective instructional design therefore requires careful coordination of visual, textual, auditory, and interactive elements to support learning without overwhelming working memory (Mayer, 2020; Sweller et al., 1998). Within such environments, AI can provide adaptive scaffolding, personalised feedback, learner modelling, predictive analytics, and dynamically adjusted learning pathways. These capabilities are also consistent with self-regulated learning perspectives, in which learners monitor their progress, respond to feedback, and adjust strategies in pursuit of learning goals (Olaleye & Vincent, 2020; Zimmerman, 2002).

Viewed together, these theoretical perspectives help explain why the convergence of AR and AI is educationally significant. AR contributes immersive visualisation, contextual interaction, and experiential engagement, while AI contributes adaptation, learner modelling, automated feedback, prediction, and decision support. Their integration therefore represents a shift from isolated educational technologies toward intelligent learning ecosystems in which learners, educators, intelligent agents, digital resources, analytics, and immersive environments interact within an interconnected system. Such ecosystems are increasingly being explored across formal education, healthcare and clinical training, professional development, workplace learning, and emerging virtual environments (Holmes et al., 2019; Lampropoulos, 2025; Luckin et al., 2022).

Recent studies suggest that AR-AI-enabled environments can support engagement, personalised learning, adaptive assistance, and simulation-based learning, while metaverse and XR-based environments further extend opportunities for collaborative and context-sensitive learning (Tene et al., 2026; Yan et al., 2025). Nevertheless, the pedagogical value of these environments depends not simply on technological sophistication, but on how effectively immersive and intelligent capabilities are aligned with learning objectives, learner needs, and instructional design.

The expansion of intelligent learning ecosystems also raises important human-centred, ethical, and inclusion-related concerns. The effectiveness of AI-supported education depends not only on predictive or algorithmic performance, but also on transparency, explainability, trust, usability, and pedagogically appropriate integration (Sullivan & Weger, 2025; Xu et al., 2025). Privacy, data governance, algorithmic bias, accessibility, and unequal access to advanced technologies are becoming increasingly important as AR-AI systems rely on richer forms of learner data and more complex automated decision-making (Baker & Hawn, 2022; Lampropoulos & Evangelidis, 2025). Human-centred design, inclusive practices, and responsible governance are therefore essential to ensuring that these technologies support rather than widen existing educational inequalities (Chalkiadakis et al., 2024; Chimbo et al., 2026).

Taken together, the literature shows substantial progress in AR, AI, and immersive educational technologies, but provides a less integrated account of how AR- and AI-related research streams are converging conceptually and structurally. Existing bibliometric studies have been particularly valuable for identifying publication growth, scholarly influence, and collaboration patterns, while systematic reviews provide detailed evidence within bounded domains (Oju et al., 2025). What remains less developed is a large-scale account that connects these structural patterns with the latent semantic organisation of the literature. The present study addresses this gap by integrating multi-database bibliometric analysis with transformer-based BERTopic modelling, allowing structural patterns and semantic themes to be examined within a common analytical framework.

## Methodology

This study employed a hybrid bibliometric and BERTopic-based approach to examine the development and convergence of AR and AI research in education. The methodological design combined bibliometric mapping, which was used to analyse the structural characteristics of the literature, including research productivity, citation influence, collaboration patterns, source dynamics, and keyword structures, with transformer-based semantic topic modelling to identify latent conceptual and thematic patterns across the literature.

The analytical focus was AR-AI convergence within educational and training contexts. Because this convergence emerged from previously distinct AR- and AI-oriented research streams, relevant studies focused primarily on either technology were retained where they contributed directly to understanding the technological, pedagogical, conceptual, or application pathways associated with AR-AI-enabled learning environments. Non-educational and purely technical studies without an educational or training dimension were excluded.

### *Data Sources and Search Strategy*

Bibliographic records were retrieved from Web of Science (WoS) and Scopus because both databases provide broad multidisciplinary coverage and structured bibliographic metadata suitable for bibliometric and large-scale literature analysis. Using both databases also reduced reliance on a single indexing source and provided broader coverage across educational technology, computer science, healthcare education, professional training, and related interdisciplinary domains. The search covered publications published between 2014 and 2024, representing a decade of substantial growth in immersive, adaptive, and AI-supported educational technologies. Only English-language records were considered.

The Web of Science search incorporated the core concepts “Augmented Reality,” “Artificial Intelligence,” and “Education.” The Scopus search used a broader TITLE-ABS-KEY strategy combining AR- and AI-related terminology with education-related terms such as *learning*, *teaching*, *pedagogy*, *training*, and *educational technology*. The broader strategy was intentionally designed to capture not only studies explicitly describing integrated AR-AI systems but also relevant research streams contributing to the emergence of AR-AI-enabled educational environments.

Studies were considered eligible when they addressed AR, AI, or their integration within an educational or training context and contributed to understanding the development, application, or conceptualisation of intelligent, adaptive, immersive, or technology-enhanced learning environments. Particular emphasis was placed on studies examining the intersection or complementary educational use of AR and AI. Studies centred exclusively on AR or AI were retained only when their content contributed meaningfully to understanding the technological, pedagogical, or application pathways underlying AR-AI convergence. Records addressing non-educational applications or purely technical system development without an educational or training dimension were excluded.

This inclusion strategy allowed the analysis to distinguish between the broader knowledge base from which AR-AI convergence has developed and the study's principal analytical focus on how these research streams increasingly intersect within education.

### Screening and Corpus Preparation

Following retrieval, records from Web of Science and Scopus were subjected to a structured screening and corpus-preparation process. A PRISMA-style workflow was used to document the progression from initial identification to the final analytical datasets. Figure 1 summarises the major stages of record identification, duplicate removal, relevance screening, validation, and preparation of the bibliometric and semantic corpora.

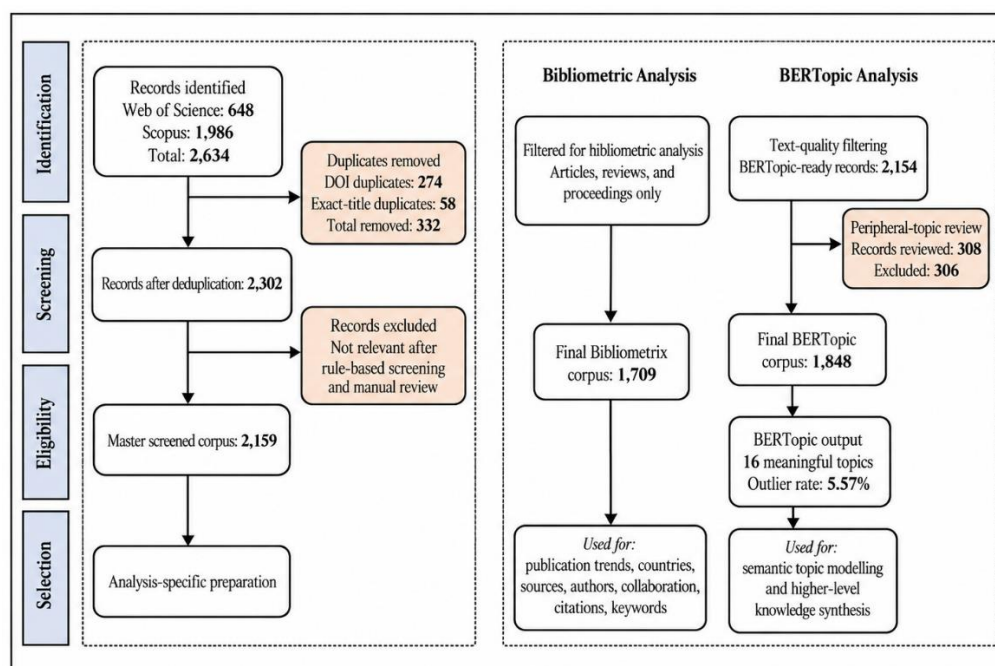


Figure 1. PRISMA-style workflow.

As illustrated in Figure 1, an initial 2,634 records were identified from Web of Science and Scopus. Duplicate records were removed through DOI- and title-based matching, after which the remaining records were screened for relevance to educational and training contexts. Screening also considered whether AR- or AI-focused publications contributed meaningfully to the wider development of AR-AI convergence rather than representing unrelated technological applications.

Following deduplication, relevance screening, and manual validation, a master screened corpus of 2,159 records was established. From this master corpus, two analytical datasets were subsequently prepared according to the different data-quality and metadata requirements of the two analytical approaches. The bibliometric corpus contained 1,709 publications, while the semantic corpus used for BERTopic modelling contained 1,848 documents.

The difference between the two analytical corpora reflects their distinct methodological requirements. Bibliometric analysis requires sufficiently complete and standardised bibliographic metadata for analyses such as authorship, citation, source, affiliation, and collaboration mapping, whereas semantic topic modelling primarily depends on the availability and quality of textual information, particularly titles, abstracts, and keywords. Maintaining separate analytical corpora therefore enabled the maximum amount of reliable information to be retained for each analytical stage without imposing identical eligibility requirements on structurally different forms of analysis.

#### *Data Processing and Bibliometric Analysis*

Records retrieved from the two databases were merged and processed to improve consistency across metadata fields. Data preparation included DOI matching, title standardisation, document-type harmonisation, keyword cleaning, and source-name harmonisation. Affiliation information was also standardised where required, and country information was extracted from author affiliations to support geographical and international collaboration analyses.

Bibliometric analysis was conducted using Bibliometrix in R, supplemented where necessary by Python-based data processing. The analysis examined several complementary dimensions of the literature, including annual publication growth, citation performance, leading publication sources, authorship patterns, geographical distribution, international collaboration, and keyword structures.

These analyses were used to characterise the structural development of AR-AI educational research over the 2014-2024 period. In particular, publication and citation trends were used to assess the growth and influence of the field, while collaboration and source analyses identified the institutional, geographical, and disciplinary environments contributing to its development. Keyword analyses provided an additional indication of how terminology and research priorities evolved as AR- and AI-related educational research became increasingly interconnected.

The bibliometric stage therefore provided the structural foundation for the subsequent semantic analysis. Whereas bibliometric indicators revealed *where*, *when*, and *through whom* the field developed, BERTopic modelling was used to examine *what* the literature was substantively addressing and how its underlying themes were organised.

#### *BERTopic Modelling and Topic Validation*

To complement the structural bibliometric analysis, *BERTopic* was employed to identify latent semantic patterns within the literature. BERTopic is a transformer-based topic-modelling approach that combines contextual document embeddings with dimensionality reduction,

density-based clustering, and class-based term weighting. Unlike methods that rely primarily on word co-occurrence, transformer embeddings enable semantically related documents to be grouped even when they use different terminology. This capability is particularly relevant to interdisciplinary research on AR and AI, where similar educational concepts may be described using terminology originating from education, computer science, healthcare, human-computer interaction, and professional training (Grootendorst, 2022; Kim & Kim, 2023).

Figure 2 presents the semantic modelling and topic-validation workflow used in the study, beginning with textual preparation and document embedding and progressing through dimensionality reduction, clustering, topic representation, and manual validation.

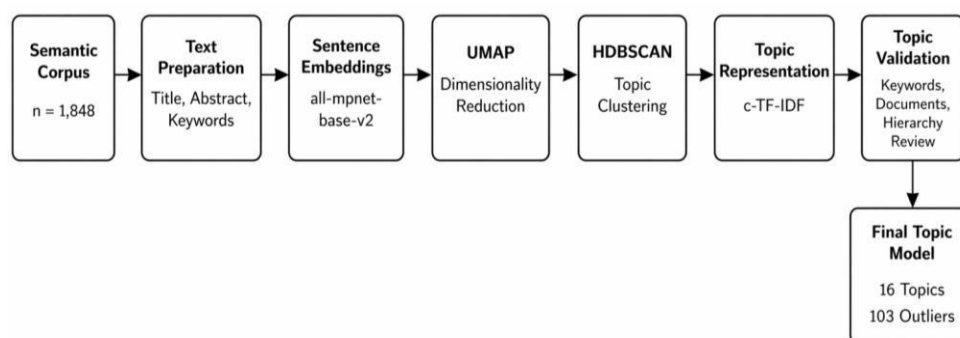


Figure 2. BERTopic modelling and topic-validation workflow.

As shown in Figure 2, document representations were generated using the all-mpnet-base-v2 sentence-transformer model. The resulting high-dimensional embeddings were reduced using Uniform Manifold Approximation and Projection (UMAP), after which HDBSCAN was applied to identify clusters of semantically related documents. BERTopic then generated interpretable topic representations using class-based term weighting.

Topic validation was undertaken through multiple complementary checks rather than relying solely on automatically generated topic labels. These checks included inspection of topic-defining keywords, examination of representative documents, assessment of semantic coherence, and review of whether the identified clusters represented substantively meaningful educational research themes. Topics that were overly peripheral, incoherent, or insufficiently related to the study's analytical focus were reviewed before the final topic structure was established.

Following validation, *16 meaningful topics* were retained for substantive interpretation. These topics were subsequently examined comparatively and synthesised into higher-level thematic groupings representing broader domains of AR-AI educational convergence.

The BERTopic stage therefore extended the bibliometric analysis from structural mapping to conceptual interpretation. Together, the two approaches enabled the study to examine both the observable research architecture of the field and the latent semantic organisation of the literature, providing a more comprehensive account of how AR- and AI-related research streams have increasingly converged into intelligent learning ecosystems.

*Integration of Bibliometric and Semantic Findings*

The final analytical stage integrated the bibliometric and BERTopic findings to develop a higher-level interpretation of the field. Bibliometric results were used to establish patterns of growth, influence, collaboration, disciplinary participation, and knowledge production, while BERTopic results identified the substantive research areas underlying those patterns.

Rather than treating the 16 topics as isolated clusters, related topics were synthesised into broader themes based on their semantic content, representative documents, technological focus, educational application, and conceptual relationships. This process resulted in five higher-level themes: *healthcare and clinical simulation; intelligent and adaptive learning systems; professional and high-risk training; human-centred, assistive, and inclusive learning; and metaverse, cultural, and emerging learning ecosystems.*

Integrating the structural and semantic analyses enabled the study to move beyond a descriptive account of publication activity and examine how different research streams collectively contribute to the emergence of AR-AI-enabled intelligent learning ecosystems. This integrated approach was subsequently used to address the four research questions concerning the field's structural development, semantic themes, evolution of intelligent learning ecosystems, and future research, practical, ethical, and policy directions.

**Bibliometric Analysis of AR-AI Educational Research**

This section examines the structural characteristics of AR-AI educational research using the bibliometric corpus of 1,709 publications indexed in Web of Science and Scopus between 2014 and 2024. The analysis focuses on publication growth, international collaboration, and scholarly influence to map the evolution of research on intelligent learning ecosystems.

*Growth and Research Landscape*

Table 1 summarises the principal characteristics of the bibliometric corpus.

Table 1

*Main Bibliometric Information*

| Indicator                      | Result    |
|--------------------------------|-----------|
| Timespan                       | 2014-2024 |
| Sources                        | 1,078     |
| Documents                      | 1,709     |
| Annual growth rate             | 39.19%    |
| Average citations per document | 20.90     |
| References                     | 149,361   |
| Author keywords                | 4,268     |
| Keywords Plus                  | 7,877     |
| Authors                        | 6,581     |
| Co-authors per document        | 4.27      |
| International co-authorships   | 9.25%     |

The dataset comprises 1,709 publications distributed across 1,078 sources and authored by 6,581 researchers. The annual growth rate of 39.19% and an average of 4.27 co-authors per document indicate a rapidly expanding and highly collaborative research domain. The large number of publication venues further suggests that AR-AI research spans multiple disciplines, including education, computer science, engineering, and healthcare. To examine temporal

growth and the contribution of the most productive countries, Figure 3 presents annual publication output alongside national production trajectories from 2014 to 2024.

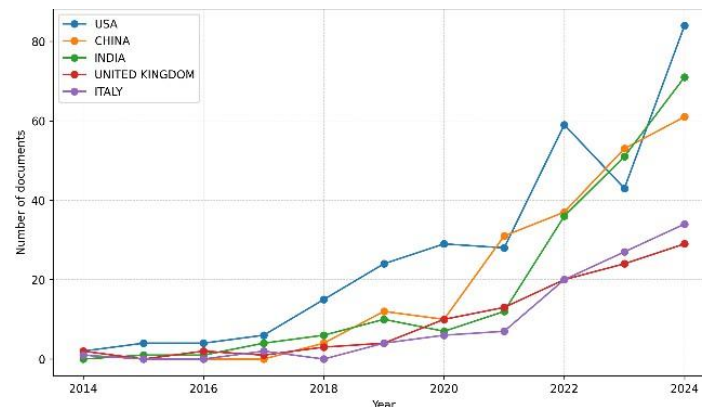


**Figure 3** Annual publication output and production trajectories of the five most productive countries (2014-2024).

Research output increased from 17 publications in 2014 to 464 publications in 2024, with particularly strong growth after 2020. The United States, China, and India emerged as the leading contributors throughout the study period, while the United Kingdom and Italy maintained consistent research activity. These trends indicate increasing global interest in AR-AI technologies and their application within intelligent learning ecosystems.

### *Geographic Collaboration*

Table 2

#### *Country Productivity and Collaboration*

| Rank | Country        | Docs | Collaboration Pair   | Freq |
|------|----------------|------|----------------------|------|
| 1    | USA            | 298  | China-USA            | 24   |
| 2    | China          | 209  | United Kingdom-USA   | 21   |
| 3    | India          | 199  | China-United Kingdom | 17   |
| 4    | United Kingdom | 109  | Italy-USA            | 16   |
| 5    | Italy          | 101  | India-Saudi Arabia   | 15   |
| 6    | Germany        | 88   | Germany-USA          | 15   |
| 7    | South Korea    | 67   | Italy-United Kingdom | 13   |
| 8    | Spain          | 61   | Italy-Spain          | 13   |
| 9    | Australia      | 58   | Spain-USA            | 12   |
| 10   | Canada         | 53   | Australia-China      | 12   |

The United States was the most productive country with 298 publications, followed by China (209) and India (199). The strongest collaboration links were observed between China and the United States, followed by partnerships involving the United Kingdom, Italy, Germany, and Australia. These patterns demonstrate increasing international engagement while also indicating that research activity remains concentrated within a relatively small group of countries. To further examine the international dimension of the field, Figure 4 visualises collaboration relationships based on authors' country affiliations.



Figure 4 International collaboration network based on country affiliations.

The collaboration network identifies the United States as the principal international hub linking major research regions, with China serving as a secondary bridging node. Despite growing global collaboration, single-country publications continue to dominate the field, suggesting opportunities for broader international research partnerships and cross-cultural validation of AR-AI learning systems.

#### Sources and Scholarly Influence

Table 3

##### Summary of Sources, Affiliations, and Keywords

| Category             | Key Results                                                  |
|----------------------|--------------------------------------------------------------|
| Productive sources   | LNCS; LNNS; IEEE Access; ACM ICPS; Applied Sciences; Sensors |
| Highly cited sources | IEEE Access; Nature; Proc. IEEE; Computers & Education: AI   |
| Productive authors   | Wang Y.; Zhang Z.; Chen X.; Liu Y.; Li J.                    |
| Key affiliations     | DFKI; NTU; Harvard; Central China Normal University          |
| Frequent keywords    | AR; AI; VR; Machine Learning; Deep Learning; Metaverse       |

The field is strongly influenced by computer science and engineering. Highly productive sources include conference proceedings and lecture-note series, while journals such as *IEEE Access* and *Computers & Education: Artificial Intelligence* demonstrate strong scholarly influence. Frequently occurring keywords include *artificial intelligence*, *augmented reality*, *virtual reality*, *machine learning*, *deep learning*, and *metaverse*, reflecting the convergence of immersive technologies and intelligent educational systems. Figure 5 compares the most productive publication sources with those achieving the greatest citation impact, allowing publication volume and scholarly influence to be considered separately.

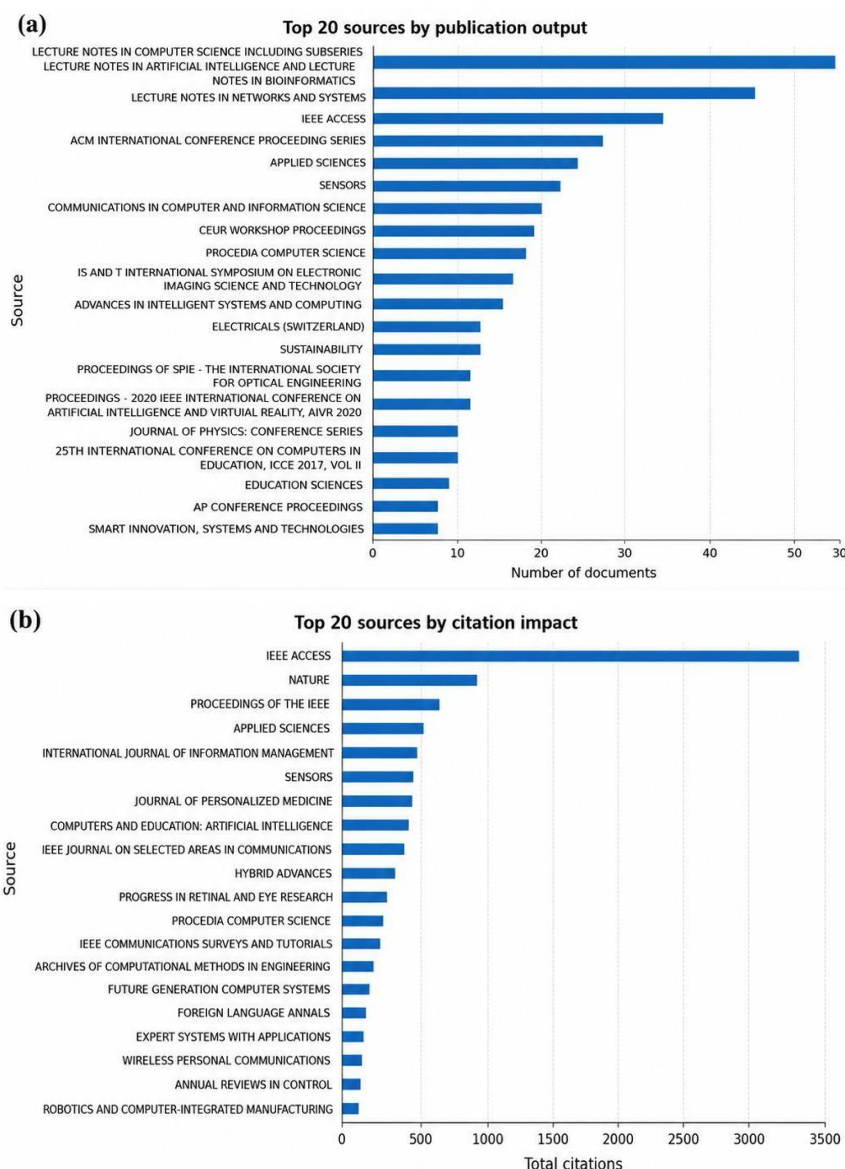


Figure 5 Comparison of source productivity and citation impact.

Conference proceedings played an important role in disseminating emerging innovations, whereas established journals generally achieved greater citation impact. This pattern suggests a dual knowledge structure in which conferences support rapid innovation and journals provide longer-term scholarly influence.

Overall, the bibliometric findings reveal a rapidly growing, internationally connected, and increasingly interdisciplinary field. While publication and collaboration patterns highlight the structural evolution of AR-AI educational research, deeper insight into its conceptual organisation requires semantic analysis, which is presented in the following section.

### *Semantic Mapping of Intelligent Learning Ecosystems*

To complement the bibliometric analysis, BERTopic modelling was applied to a semantic corpus of 1,848 documents. Whereas bibliometric indicators reveal structural characteristics of the field, BERTopic uncovers latent thematic patterns within the literature. The final model

produced 16 meaningful topics, providing insight into how AR and AI are being applied across educational, professional, and emerging learning contexts.

### *Topic Distribution*

Table 4

#### *BERTopic Topic Interpretation*

| Topic | Topic label                   | Documents |
|-------|-------------------------------|-----------|
| 0     | Healthcare Education          | 528       |
| 1     | Intelligent Learning Systems  | 481       |
| 2     | Metaverse Ecosystems          | 100       |
| 3     | Computer Vision               | 98        |
| 4     | Smart Learning Infrastructure | 74        |
| 5     | Industrial Training           | 73        |
| 6     | Human-AI Interaction          | 63        |
| 7     | Cultural Learning             | 59        |
| 8     | Rehabilitation                | 49        |
| 9     | Workforce Development         | 42        |
| 10    | Construction Training         | 37        |
| 11    | High-Risk Training            | 32        |
| 12    | Assistive Education           | 31        |
| 13    | Clinical Education            | 29        |
| 14    | Virtual Learning Environments | 28        |
| 15    | Sports Training               | 21        |

The topic distribution reveals a highly concentrated research landscape. Two dominant topics, Healthcare Education (Topic 0) and Intelligent Learning Systems (Topic 1), account for more than half of the semantic corpus, indicating that healthcare simulation and adaptive learning represent the primary areas of AR-AI educational research.

The remaining topics demonstrate the increasing diversification of the field, encompassing metaverse learning, human-AI interaction, smart learning infrastructures, industrial and professional training, assistive education, cultural heritage learning, construction and high-risk training, rehabilitation, and workforce development. Collectively, these topics suggest that AR-AI applications have expanded well beyond traditional classroom settings into a broad range of educational and training environments.

### *Topic Relationships*

The relationships among topics were explored using intertopic distance mapping and hierarchical clustering. Figure 6 presents the intertopic distance map used to examine semantic proximity among the 16 BERTopic clusters.

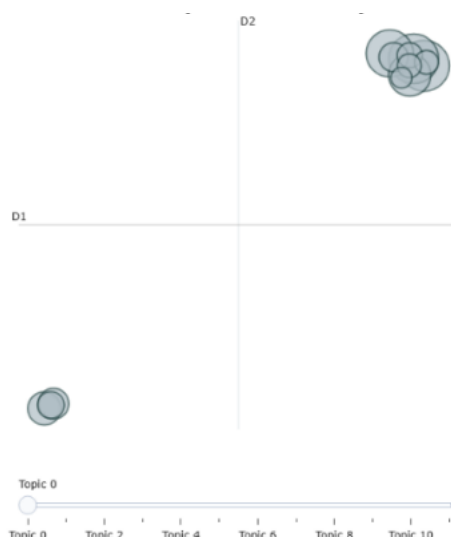


Figure 6 Intertopic distance map showing semantic relationships among BERTopic clusters.

Figure 6 reveals several closely related thematic groupings. Healthcare education, clinical practice, rehabilitation, and assistive learning topics occupy neighbouring positions, reflecting common interests in simulation, learner support, and skill development. Similarly, intelligent learning environments, learning analytics, IoT-supported systems, and human-AI interaction topics demonstrate strong conceptual connections centred on adaptation, personalization, and learner-centred support. To examine these relationships at a higher level of abstraction, Figure 7 presents the hierarchical clustering of the identified BERTopic topics.

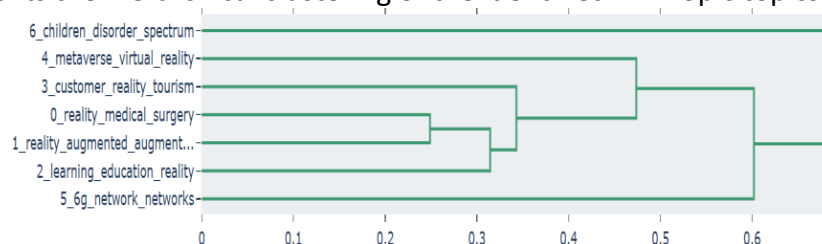


Figure 7 Hierarchical clustering of BERTopic topics showing higher-level thematic relationships.

The hierarchical structure shown in Figure 7 further indicates that individual topics can be grouped into broader domains. Healthcare-related topics form one major cluster, while intelligent learning systems, analytics, and adaptive technologies form another. Another thematic cluster reflects the growing application of AR-AI in occupational and practice-based settings, particularly industrial maintenance, construction, aviation, and workforce development. Human-centred and assistive applications emerge as a related cluster, while metaverse, cultural heritage, and immersive virtual environments represent a distinct frontier of research.

Overall, the topic relationships demonstrate that AR-AI research is increasingly organised around interconnected intelligent learning ecosystems rather than isolated technological applications. These higher-level relationships provide the foundation for the thematic synthesis presented in the next section.

### *Knowledge Synthesis: Intelligent Learning Ecosystems*

The BERTopic analysis identified 16 topics that were synthesised into five higher-level thematic domains, providing a conceptual view of how AR and AI are shaping intelligent learning ecosystems across educational and training contexts.

*Healthcare and clinical simulation* represents the largest and most established domain, encompassing medical education, clinical training, rehabilitation, and patient-centred learning, where immersive visualisation and intelligent feedback support skill development and professional practice.

*Intelligent and adaptive learning systems* comprise research on personalised learning environments, learning analytics, intelligent tutoring systems, and AI-enabled educational support, highlighting the growing role of adaptive technologies in learner-centred education. *Professional and high-risk training* includes industrial, construction, high-risk, and workforce development applications, where AR-AI technologies are used to support procedural learning, decision-making, and performance in authentic environments.

*Human-centred, assistive, and inclusive learning* integrates human-AI interaction, assistive technologies, special education, rehabilitation, and accessibility-focused applications, reflecting growing attention to usability, inclusion, and learner diversity.

*Metaverse, cultural, and emerging learning ecosystems* encompass metaverse-based learning, cultural heritage education, and other exploratory applications that combine immersive environments, intelligent systems, and collaborative digital experiences. Building on the topic distribution and hierarchical relationships, Figure 8 synthesises the identified topics into five higher-level domains of AR-AI-enabled intelligent learning ecosystems.

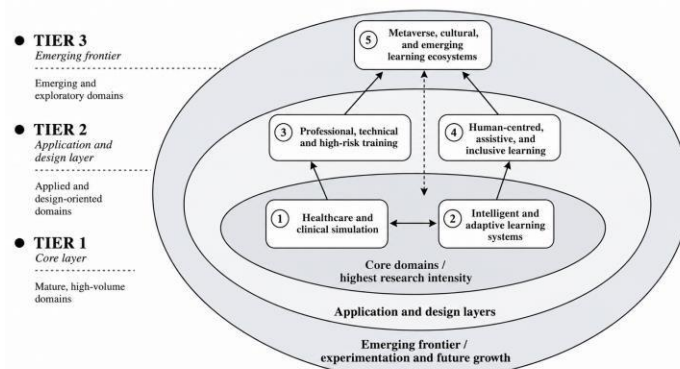


Figure 8 Conceptual framework showing the five thematic domains of AR-AI-enabled intelligent learning ecosystems.

Collectively, these themes indicate that AR-AI research is evolving beyond standalone technologies toward integrated ecosystems that combine immersion, adaptation, analytics, collaboration, and learner support. The synthesis provides a higher-level understanding of the field and establishes the foundation for discussing the implications and future directions of AR-AI-enabled intelligent learning ecosystems.

### Discussion, Implications, and Future Directions

The findings indicate that AR-AI educational research has developed into a rapidly expanding and increasingly interdisciplinary field organised around intelligent learning ecosystems. Bibliometric evidence showed substantial growth in publication output and international participation, while BERTopic analysis identified healthcare education and intelligent learning systems as the most prominent thematic areas. At the same time, professional training, assistive technologies, human-AI interaction, and immersive virtual environments emerged as important areas of diversification. Together, these patterns indicate a movement away from isolated applications of AR or AI toward learning environments in which immersive interaction, adaptive intelligence, analytics, and learner support are increasingly integrated. These findings extend previous reviews that documented the growth of AR, AI, and immersive technologies largely as individual research domains. Earlier studies identified increasing educational adoption of AR and AI across diverse contexts (Anesti & Irwanto, 2025; Ikram et al., 2026; Singh et al., 2024), whereas the present analysis shows that their research trajectories increasingly intersect around adaptive learning, healthcare simulation, human-AI interaction, professional training, and immersive learning environments. The prominence of healthcare education and intelligent learning systems suggests that convergence is developing most strongly in contexts where immersive representation can be combined with personalised feedback, simulation, learner modelling, analytics, and decision support. This supports the view that the educational significance of AR-AI lies not simply in the co-occurrence of two technologies, but in their complementary capacity to support context-aware and adaptive learning experiences.

The methodological findings also demonstrate the value of integrating bibliometric analysis with transformer-based semantic modelling. Bibliometric techniques revealed the structural characteristics of the field, including publication growth, collaboration patterns, source influence, and geographical participation, whereas BERTopic provided insight into its latent conceptual organisation. Combining these approaches therefore enabled structural patterns to be interpreted alongside the substantive themes underlying them, offering a more comprehensive account of how AR-AI educational research is developing than either method could provide independently (Kim & Kim, 2023; Lampropoulos & Evangelidis, 2025).

From a practical perspective, the findings have implications for educators, instructional designers, and technology developers. The prominence of healthcare simulation, adaptive learning, and professional training suggests that AR-AI systems are particularly relevant where learning requires visualisation, contextual practice, feedback, and repeated decision-making. However, technological sophistication alone does not ensure educational value. AR-AI environments should be aligned with pedagogical objectives, learner characteristics, assessment needs, and instructional design principles to ensure that immersive and adaptive features support rather than distract from learning (Lampropoulos, 2025; Tene et al., 2024). The emergence of human-centred and assistive themes further highlights the importance of accessibility, usability, learner diversity, and inclusive design when developing intelligent learning environments.

The findings also have ethical and policy implications. As AR-AI environments increasingly incorporate learner modelling, automated feedback, analytics, and adaptive decision-making, issues of privacy, transparency, explainability, algorithmic bias, data governance,

accessibility, and equitable access become increasingly significant. Educational institutions and policymakers should therefore ensure that technological adoption is accompanied by appropriate governance mechanisms, transparent data practices, and safeguards for learners, particularly where automated systems influence instructional decisions or access to educational support (Baker & Hawn, 2022; Lampropoulos & Evangelidis, 2025; Xu et al., 2025).

Future research should extend the field in several directions. Longitudinal studies are needed to determine whether the benefits associated with AR-AI environments are sustained over time and across different learner populations. Greater cross-institutional and international collaboration would also support validation across cultural, disciplinary, and socioeconomic contexts. Emerging areas such as metaverse-based learning, embodied interaction, assistive educational technologies, and advanced human-AI collaboration warrant further investigation. Future work should also examine how adaptive and immersive functions influence learning processes, engagement, decision-making, and instructional effectiveness rather than focusing primarily on technological novelty.

The study is subject to certain limitations. The analysis was restricted to English-language publications indexed in Web of Science and Scopus between 2014 and 2024, and therefore may not capture relevant studies indexed elsewhere or published in other languages. In addition, bibliometric and topic-modelling approaches identify patterns within the published literature but do not directly establish the educational effectiveness of AR-AI interventions. The findings should therefore be interpreted as a structural and conceptual synthesis of the research landscape rather than as evidence of causal learning effects. Despite these limitations, the study provides a broad account of the evolution, thematic organisation, and emerging directions of AR-AI educational research and offers a foundation for further empirical, methodological, and policy-oriented investigation.

## Conclusion

This study mapped the structural and conceptual development of AR-AI educational research from 2014 to 2024 using an integrated bibliometric and BERTopic approach. The findings reveal substantial growth and increasing interdisciplinary and international participation, alongside a thematic landscape dominated by healthcare education and intelligent learning systems and complemented by emerging applications in professional training, human-AI interaction, assistive technologies, and immersive environments.

The synthesis of 16 topics into five higher-level domains indicates that AR- and AI-related research is increasingly intersecting around learning environments that combine immersion, adaptation, analytics, intelligent support, and human-centred interaction. Methodologically, integrating bibliometric mapping with transformer-based semantic modelling provides complementary structural and conceptual perspectives on this evolving field. Future research should strengthen cross-context validation, longitudinal evaluation, responsible AI governance, accessibility, and international collaboration as AR-AI-enabled learning ecosystems continue to develop.

**Ethical Statement**

This study was based exclusively on published bibliographic records retrieved from Web of Science and Scopus and did not involve human participants, primary data collection, or experimental procedures. Formal ethical approval and informed consent were therefore not required.

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**Competing Interests**

The authors declare that they have no known financial or non-financial competing interests that could have influenced the work reported in this manuscript.

**Author Contributions**

Joseph Uzuazomaro Oju conceptualised the study, conducted the data retrieval, screening, bibliometric analysis, BERTopic modelling, interpretation of findings, and preparation of the initial manuscript. Olufunke Rebecca Vincent contributed to conceptual refinement, educational interpretation, supervision, and critical review of the manuscript. Gregory O. Onwodi contributed to methodological review, interpretation of findings, and manuscript revision. All authors reviewed and approved the final manuscript.

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