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A bibliometric analysis of immersive environments in STEM education: Global trends, research structure, and thematic evolution

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Abstract: This study presents a comprehensive bibliometric analysis of immersive environments in STEM education, examining global research trends, intellectual structures, and thematic developments within the field. Using a dataset of 100 Scopus-indexed publications screened through PRISMA procedures, the analysis employed performance indicators, citation metrics, co-occurrence networks, and thematic mapping to evaluate the evolution of immersive technologies, including VR, AR, MR, and XR in STEM learning contexts. The results reveal a steady increase in annual scientific production, highlighting the growing integration of immersive tools to enhance engagement, conceptual understanding, and experiential learning in science and engineering education. Key research clusters emphasize simulation-based learning, virtual laboratories, and engineering applications, while foundational themes such as VR/AR for student learning remain conceptually broad and require further theoretical refinement. Geographic patterns indicate strong contributions from technologically advanced countries, with emerging participation from diverse regions. The thematic map identifies well-developed motor themes alongside emerging areas such as personalized immersive training and early-stage metaverse applications. Overall, the findings demonstrate that immersive technologies have transitioned from experimental innovations to influential components of modern STEM pedagogy. Future research should strengthen theoretical integration, methodological rigor, and equitable access to immersive learning ecosystems to fully realize their transformative potential in STEM education.

Keywords: *Augmented Reality, Bibliometric Analysis, Immersive Learning, Scientometric Mapping, Simulation-Based Learning, STEM Education, Virtual Reality.*

1. Introduction

Immersive technologies such as virtual reality (VR), augmented reality (AR), mixed reality (MR), and extended reality (XR) have increasingly transformed STEM education by providing authentic, interactive, and experiential learning environments that enhance engagement and conceptual understanding [1-3]. These technologies support project-based and informal learning, enabling learners to participate in creative and collaborative STEM practices through immersive multimodal platforms [1]. XR applications specifically designed for STEM learning have demonstrated significant improvements in instructional design quality, cognitive engagement, and user experience across science and engineering domains [2]. Immersive VR has further contributed to more inclusive and accessible STEM education by supporting neurodivergent learners in cybersecurity programs through embodied and interactive environments [3]. Cross-cultural STEM learning collaborations have also benefited from immersive online platforms, strengthening culturally responsive teaching practices and collaborative problem-solving skills among teacher candidates [4].

Immersive environments facilitate authentic STEM inquiry by enabling learners to interact with real-world scientific problems, such as client-based tasks that enhance communication, contextual reasoning, and scientific modeling processes [5]. Mixed-reality systems further support

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sustainability-oriented STEM learning by enriching user experience and promoting continued engagement through graphical visualization and immersive information design [6]. Game-based virtual environments have demonstrated potential to enhance representational flexibility and cognitive processing among autistic adolescents engaged in STEM-related tasks within immersive virtual worlds [7]. VR field-trip experiences have enhanced learners' sense of agency and identity formation in scientific contexts, reinforcing immersive tools' ability to situate learners within authentic scientific environments [8]. Additionally, immersive VR has been shown to empower English language learners in STEM education by providing interactive, language-integrated scientific content and virtual experimentation opportunities [9].

Interactive learning strategies informed by learning analytics have demonstrated that immersive environments can improve STEM students' collaborative problem-solving, higher-order thinking, and engagement with complex instructional materials [10, 11]. VR dissection systems used in physiology education have effectively improved conceptual understanding and procedural knowledge, demonstrating the value of immersive simulation for laboratory-intensive STEM disciplines [12]. Immersive VR environments used for drone programming instruction support integrated engineering learning by combining coding, simulation, and spatial visualization in a unified experiential platform [13]. Intensive STEM programs incorporating immersive activities have shown increased skill development, knowledge acquisition, and interest among diverse student groups [14]. In primary education, VR-supported STEM project-based tasks have enhanced creativity, engineering design thinking, and the integration of STEM competencies [15].

Immersive VR systems have also expanded access to STEM career exploration by offering virtual field experiences that connect learners with real-world industry contexts in accessible ways [16]. Biomedical engineering programs have benefited from VR laboratory supplements that address limitations in cost, safety, and access while providing high-quality experiential practice [17]. Immersive learning environments have also supported self-assessment processes among undergraduate STEM learners by offering scalable, flexible virtual evaluation experiences [18]. A comprehensive systematic review confirms that immersive VR technologies contribute positively to STEM learning outcomes, motivation, and user experience, while also identifying several implementation challenges [19]. In-depth analysis of learners' time allocation within immersive simulations provides insights into behavioral patterns and performance indicators critical to STEM competency development [20]. Immersive mixed-reality collaborations have demonstrated effectiveness in improving digital literacy and computational thinking through interactive university–school partnerships [21]. Emerging VR-based science learning environments have further highlighted the importance of emotional engagement, identity exploration, and embodied learning processes in shaping STEM learning experiences [22].

Despite these advances, the rapid expansion of immersive technologies across STEM disciplines has led to a fragmented research landscape characterized by diverse methodologies, disciplinary silos, and inconsistent reporting structures [1-12]. Although individual studies contribute valuable insights, there remains a lack of comprehensive, data-driven analysis that maps global research trends, identifies influential contributors, and synthesizes thematic developments across the field [1-22]. As immersive STEM education continues to evolve at an accelerated pace, a bibliometric analysis is urgently needed to provide a structured overview of the field's intellectual development and to identify future research opportunities [14-20].

2. Measure of Outcome

The outcomes of this bibliometric investigation were measured using a structured set of indicators aligned directly with the empirical results presented in Figures 1–11 and Table 1. These outcome measures were designed to evaluate the productivity, scientific influence, conceptual structure, and thematic evolution of immersive environment research in STEM education. Each indicator corresponds to a specific visualization or analytical output in the Results section, ensuring coherence between methodological measurement and empirical findings.

2.1. Screening and Dataset Composition Indicators

The first group of outcome measures focuses on dataset refinement and eligibility, as reflected in Figure 1 (PRISMA Flow Diagram) and Table 1. These indicators include:

- Total Records Identified from Scopus
- Number of Excluded Studies based on relevance, language, and metadata
- Final Number of Included Articles forming the core analytical dataset

These measures ensure transparency of data selection and validate the representativeness of the final 100-article corpus used in subsequent analyses.

2.2. Descriptive Performance Indicators

The second category evaluates the general productivity and structural characteristics of the field and corresponds directly to Figure 2 (Main Information of the Dataset) and Figure 3 (Annual Scientific Production). Key indicators include:

- Annual Publication Output, measuring growth trends over time
- Number of Sources (Journals/Conferences) contributing to the field
- Total Authors and Authorship Patterns, indicating collaboration intensity
- Document Types, showing how research outputs are distributed across publication formats

These measures describe the size, evolution, and collaborative nature of the research landscape.

2.3. Intellectual and Publication Structure Indicators

These indicators map the relationships among authors, journals, and keywords, corresponding to Figure 4 (Three-Field Plot) and Figure 5 (Most Relevant Sources):

- Author–Source–Keyword Linkages, showing how scholarly communities interact
- Core Publication Venues, identifying journals with the highest contribution
- Authorship Concentration, revealing influential researchers and institutional clusters

These outcomes highlight where foundational conversations in immersive STEM education occur and how intellectual communities organize around key topics.

2.4. Geographic and Global Contribution Indicators

To measure the international distribution and scientific leadership within the field, the study extracted indicators represented in Figure 6 (Corresponding Author's Countries) and Figure 7 (Countries' Scientific Production):

- Country-Level Publication Output, identifying leading nations
- Corresponding Author Distribution, measuring geographic leadership
- Patterns of Global Participation, indicating emerging regions in immersive STEM research

These indicators reveal how immersive learning research is globally distributed and which countries serve as central drivers of innovation.

2.5. Conceptual Structure Indicators

These indicators evaluate the core concepts, dominant research themes, and recurring terminologies used across the dataset. The corresponding results are shown in Figure 8 (Most Frequent Words) and Figure 9 (Word Cloud).

- Keyword Frequency, identifying dominant constructs
- Lexical prominence, revealing emphasis areas in the research discourse.
- Conceptual focus areas, such as VR learning, STEM competencies, simulation, engagement, and virtual laboratories.

These measures outline the conceptual foundation upon which immersive STEM education research is built.

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2.6. Knowledge Network and Relationship Indicators

Indicators of conceptual interconnection and research clustering correspond directly to Figure 10 (Keyword Co-occurrence Network).

- Co-Occurrence Strength, measuring how often keywords appear together
- Cluster Formation, identifying conceptual communities
- Network Density, indicating how strongly themes connect within the body of literature

These outcomes highlight the structure of knowledge and reveal how technological, pedagogical, and disciplinary concepts interact within immersive STEM research.

2.7. Thematic Development and Strategic Positioning Indicators

The final group measures the thematic evolution of the field and aligns with Figure 11 (Thematic Map):

- Theme Centrality, indicating importance within the overall research domain
- Theme Density, indicating the internal development and cohesion of a theme
- Classification of Themes into
- Motor Themes (highly developed, highly central)
- Basic Themes (central but underdeveloped)
- Niche Themes (specialized but less influential)
- Emerging/Declining Themes (low centrality and density)

These indicators provide strategic insights into which areas are foundational, which are growing, and which represent future opportunities for immersive STEM education research.

3. Materials and Methods

3.1. Research Design

This study employed a bibliometric research design to systematically analyze the global scientific literature on the use of immersive environments in STEM education. Bibliometric analysis enables the quantitative examination of publication patterns, influential contributors, conceptual structures, and thematic evolution within a research domain. The study followed internationally accepted reporting standards, including the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, to ensure transparency and reproducibility [23].

3.2. Data Source and Search Strategy

The Scopus database was selected as the primary data source due to its extensive coverage of peer-reviewed publications across science, technology, and education. The search query combined keywords related to immersive technologies and STEM education. All document types were initially included, and no time restrictions were applied to maximize dataset comprehensiveness.

The search yielded 286 records, which were exported in BibTeX and CSV formats for further analysis. Duplicate checking and eligibility screening followed PRISMA guidelines.

3.3. Eligibility Criteria

The inclusion and exclusion criteria were defined as follows:

- Inclusion criteria

1. Articles written in English
2. Studies focusing on immersive environments (e.g., VR, AR, MR, virtual labs, simulations).
3. Research situated within STEM education contexts
4. Peer-reviewed journal articles or conference papers

- Exclusion criteria

1. Non-English documents
2. Articles unrelated to immersive environments

3. Publications outside STEM education
4. Duplicates and incomplete metadata

After screening, 100 articles met all inclusion criteria.

3.4. Data Extraction

Data extraction included bibliographic fields such as title, authors, affiliations, abstract, keywords, source title, country, citations, and publication year. This information was used to generate descriptive, thematic, and structural bibliometric indicators.

3.5. Data Analysis

The dataset was analyzed using the Bibliometrix package in R and the Biblioshiny web interface to produce general descriptive statistics, annual publication trends, country contributions, keyword frequencies, thematic maps, and network visualizations.

The analysis involved:

- Performance analysis
- Annual scientific production
- Most relevant authors and sources
- Country scientific output
- Science mapping analysis
- Keyword co-occurrence networks
- Thematic evolution
- Three-field plots linking authors, institutions, and keywords

All results are reported visually through Figures 1–10, with detailed descriptions below.

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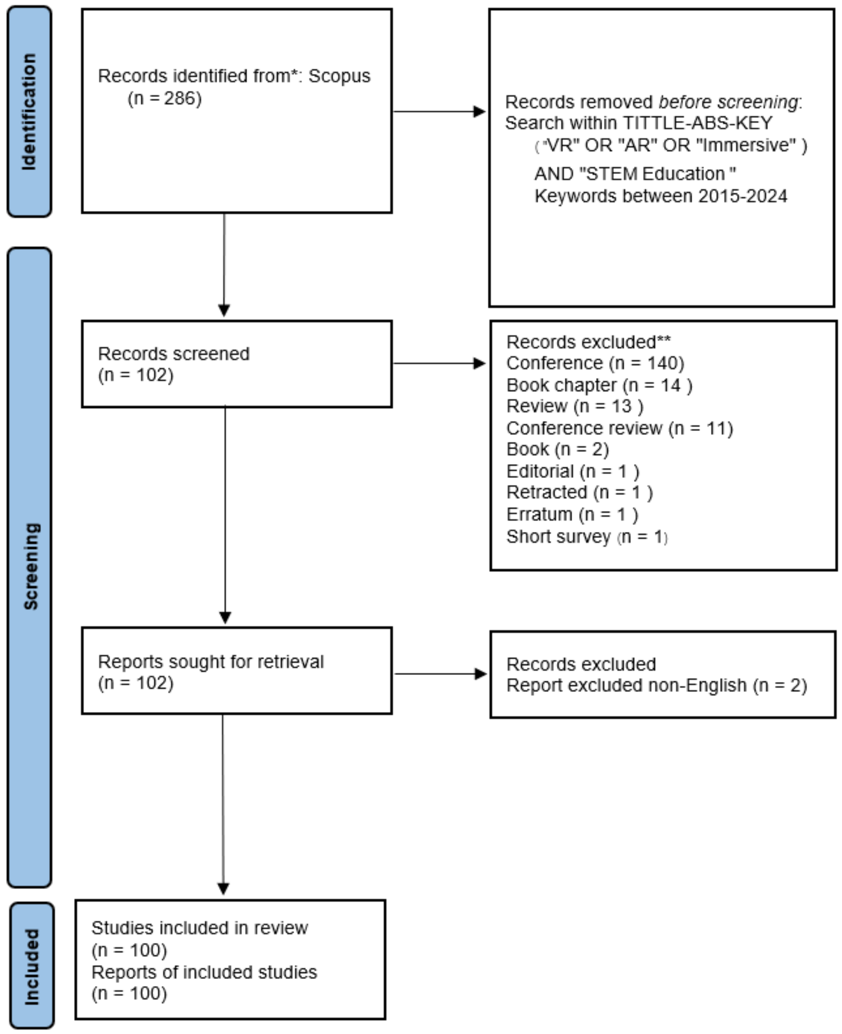

Figure 1.
Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Flow Diagram.

Figure 1 presents the PRISMA flow diagram, which visually summarizes the screening and selection procedure described in Table 1. The diagram follows the standard PRISMA structure, beginning with the identification of records in the Scopus database, proceeding through stages of screening and eligibility assessment, and ending with the final inclusion of articles. Each box in the diagram corresponds to a distinct phase: identification, screening, eligibility, and inclusion, and is connected by directional arrows, thereby illustrating the logical sequence of decisions made throughout the process.

This figure plays an essential methodological role in enhancing the study's transparency and credibility. By clearly showing how the 286 initially identified records were gradually reduced to 100 eligible studies, Figure 1 allows readers to evaluate the rigor of the inclusion and exclusion criteria and the potential for selection bias. The explicit reporting of reasons for exclusion, such as irrelevance to the topic or non-English language, helps reassure readers that the final dataset is not arbitrarily assembled but the result of a well-defined, replicable procedure. In the context of bibliometric research, where the dataset's composition directly affects subsequent analyses, such a flow diagram is essential for establishing methodological robustness and aligning the study with best practices in systematic evidence synthesis.

Table 1.
Technical Summary.

Step	Total Records	Excluded	Remaining
Identified from Scopus	286	–	286
After applying the exclusion criteria	–	184	102
Excluded (non-English)	–	2	100
Final Included Studies	–	–	100

Table 1 provides a concise yet critical overview of the document selection and refinement process used in this bibliometric study. The table traces the flow of records from the initial identification in the Scopus database to the final set of articles included in the analysis. At the first stage, 286 records were retrieved, representing the broad landscape of publications potentially related to immersive environments in STEM education. This initial pool captures a wide variety of document types, topics, and quality levels, ensuring that the subsequent screening process starts from a comprehensive universe of research outputs.

The second stage in Table 1 reflects the application of the predefined exclusion criteria. A total of 184 records were excluded at this point because they did not meet the inclusion criteria (e.g., being outside the STEM education context, not focusing on immersive environments, or lacking sufficient bibliographic information). This reduction to 102 remaining records indicates that a substantial proportion of the initially retrieved literature was tangential or irrelevant to the study's specific focus, highlighting the necessity of rigorous screening in bibliometric research. Subsequently, two non-English articles were removed, leaving 100 final studies that formed the core dataset for analysis. This final corpus is sufficiently large to allow meaningful bibliometric patterns to emerge, while remaining focused and conceptually coherent. Overall, Table 1 demonstrates that the dataset results from a transparent, systematic, and reproducible selection process, thereby ensuring the reliability and validity of subsequent findings.

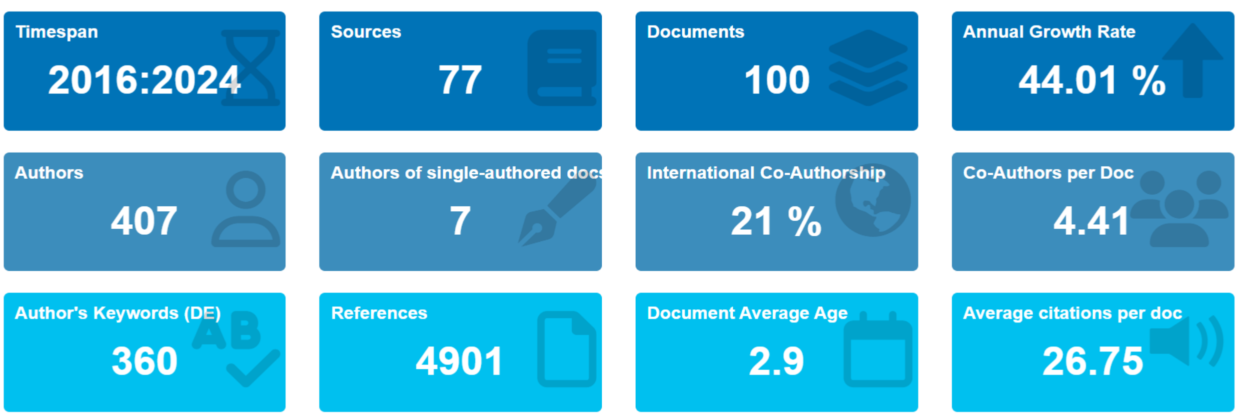

Figure 2.
Main Information of the Dataset

Figure 2 presents the main descriptive information of the bibliometric dataset, offering a global snapshot of its structural characteristics. Typically, this figure compiles statistics such as the total number of documents, the number of sources (journals and conference proceedings), the total number of authors, average citations per document, document types, and the average number of authors per article. By summarizing these metrics in a single visual, the figure enables readers to quickly grasp the scope and complexity of the research field under investigation.

The information in Figure 2 is crucial for understanding the foundational landscape of immersive environment research in STEM education. For instance, the number of sources and authors provides insight into how widely the topic has diffused across different publication outlets and academic communities. A high average number of authors per document may suggest a collaborative and interdisciplinary nature of the field. In contrast, the distribution of document types can signal whether research is more often published as journal articles, conference papers, or other formats. Moreover, average citation counts provide an initial proxy for the field's overall impact and visibility. Together, these indicators help position the domain in terms of maturity, productivity, and scholarly engagement, serving as a baseline for more specialized analyses reported in later figures.

4. Statistical Analysis

The statistical analysis in this study used a combination of performance analysis and science-mapping techniques, following established bibliometric procedures to quantify research productivity, intellectual structure, and thematic evolution within the domain of immersive environments in STEM education. All computations and visualizations were performed using the Bibliometrix package (version R) and its web interface Biblioshiny, which provides reproducible analytical workflows for processing and interpreting large bibliographic datasets.

4.1. Performance Analysis

Performance analysis focused on descriptive statistical indicators that summarize the dataset's overall structure. This included:

- The total number of documents, authors, and sources
- Annual scientific production
- Authorship patterns
- Institutional and country-level contributions
- Most relevant publication venues
- Most frequent keywords within the corpus

These metrics enabled the study to examine publication growth trends (Figure 3), dominant outlets (Figure 5), and geographic patterns of research productivity (Figures 6 and 7). Citation-based indicators were also reviewed to understand the distribution of academic impact across authors, journals, and countries.

4.2. Science Mapping Analysis

To explore deeper conceptual relationships within the field, science mapping techniques were employed. These methods uncover structural patterns and interconnections among keywords, authors, institutions, and sources. The following analyses were conducted:

- Three-field plot (authors–sources–keywords) to illustrate intellectual linkages (Figure 4)
- Keyword frequency analysis to identify dominant research concepts (Figure 8)
- Word cloud visualization to highlight the prominence of key terms (Figure 9)
- Co-occurrence network analysis to detect conceptual clusters and research communities (Figure 10)
- Thematic mapping to classify themes as motor, niche, basic, or emerging/declining (Figure 11)

Network matrices were constructed using co-word analysis, where the co-occurrence of author keywords across documents was calculated and normalized using association strength measures. Clustering algorithms, primarily the Louvain modularity method, were applied to detect keyword communities within the co-occurrence graph. Centrality and density values were computed to generate the thematic map, enabling the identification of highly developed themes, emerging topics, and structural gaps in the literature.

4.3. Data Cleaning and Standardization

Statistical validity was ensured through a rigorous pre-processing phase in which:

- Duplicated entries were removed
- Author names were standardized (e.g., initials merging, spelling variations correction)
- Keywords were harmonized (e.g., "VR," "virtual reality," and "virtual-reality" merged into one)
- Metadata fields (countries, affiliations, sources) were normalized

This cleaning process helped prevent fragmentation in network analysis and ensured accurate clustering in the co-occurrence and thematic mapping procedures.

4.4. Interpretation Framework

The results were interpreted based on the combined output of descriptive indicators and structural analyses. Performance metrics reveal who contributes to the field and how much, while science mapping visualizes how research topics relate, which themes are central, and which areas are emerging. Together, these analyses provide a multi-dimensional understanding of the published literature, allowing insights into both the developmental trajectory and the conceptual architecture of immersive STEM education research.

5. Results

5.1. Annual Scientific Production

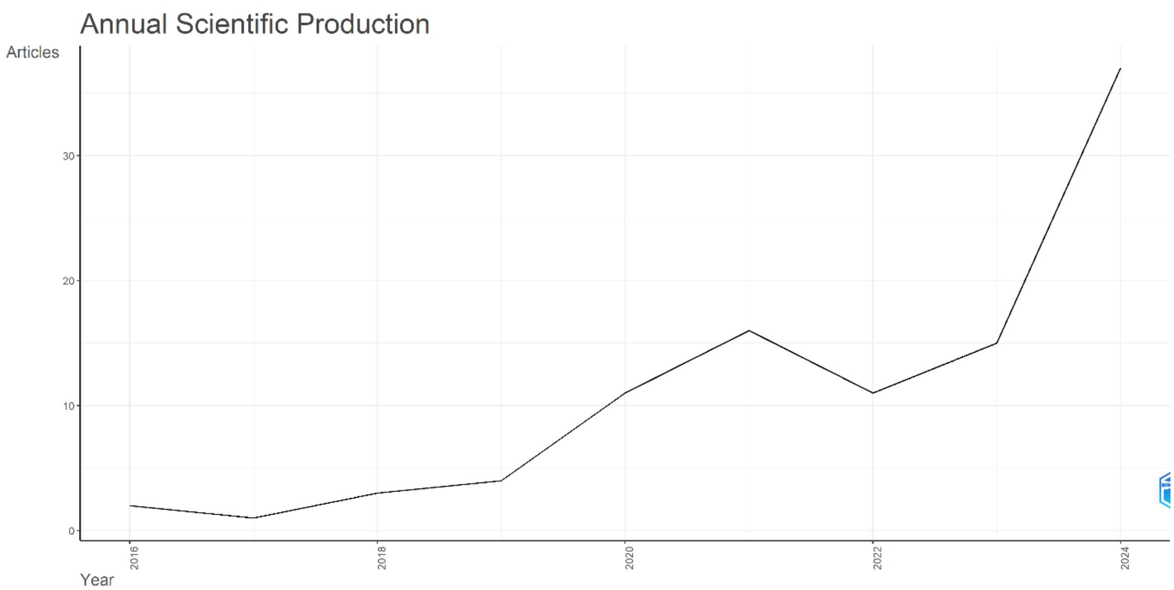

Figure 3.
Annual Scientific Production.

Figure 3 illustrates the annual scientific production, displaying the number of publications per year within the domain of immersive environments in STEM education. The horizontal axis represents the publication years, while the vertical axis shows the corresponding number of documents. This temporal distribution allows readers to visualize the growth trajectory of research interest in this area over time.

Interpreting Figure 3 provides several key insights. A clear upward trend in the number of publications suggests that immersive technologies are becoming increasingly central to STEM education research, potentially driven by technological advancements, greater accessibility of VR/AR tools, and the integration of digital learning environments into curricula. Periods of rapid growth may correspond to milestones such as the introduction of new VR/AR devices, global educational reforms, or

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increased funding for digital learning initiatives. Conversely, any plateau or decline in the curve could indicate stabilization of the field or shifting research priorities. By highlighting these dynamics, Figure 3 does not merely count publications; it reveals the temporal evolution of scholarly attention and helps situate the current study within a broader historical context of educational technology development.

5.2. Mapping Authors, Sources, and Keywords (Three-Field Plot)

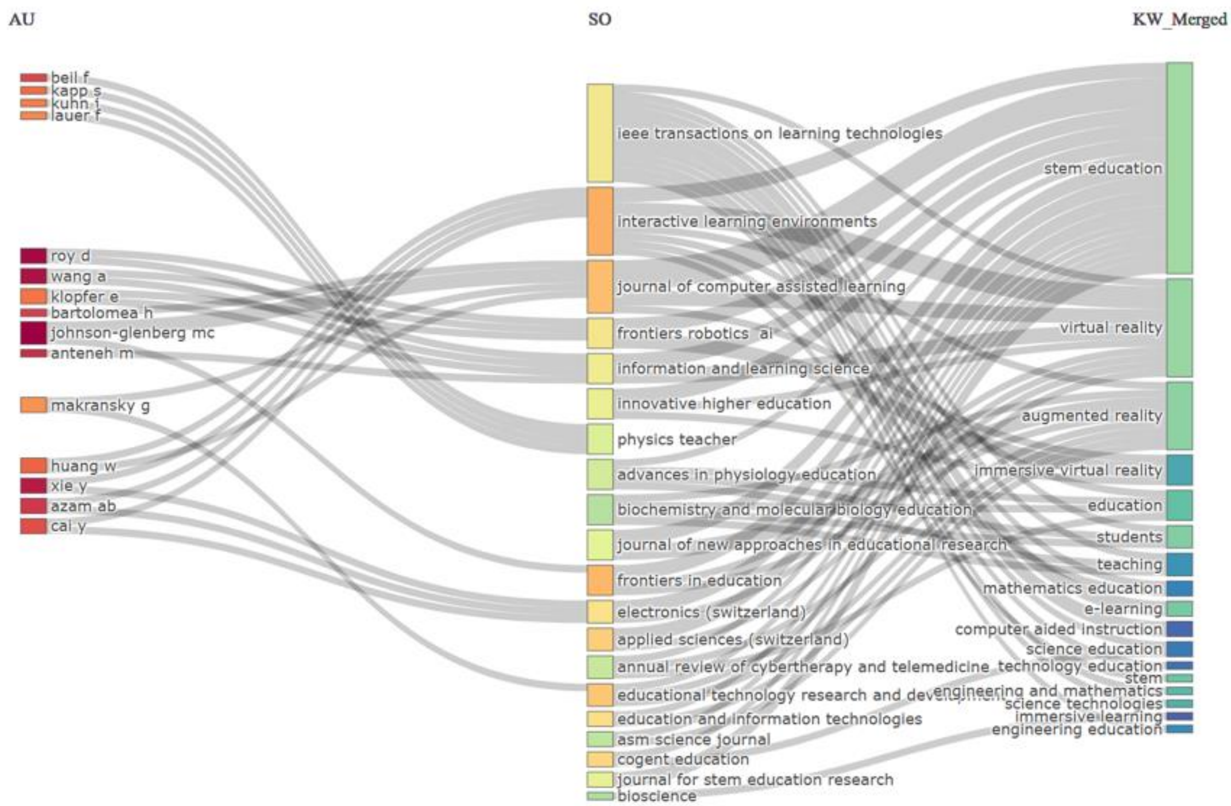

Figure 4.
Three-Field Plot (Authors–Sources–Keywords).

Figure 4 presents a three-field plot that visualizes the relationships between three core elements of the bibliometric dataset: authors, publication sources (journals or conferences), and keywords. Typically arranged as three vertical columns, the plot shows the most productive authors on one side, the most influential or frequently used sources in the middle, and the most recurrent keywords on the other side. Lines connecting these three fields indicate which authors publish in which sources and what keywords they frequently use.

This figure is particularly powerful for uncovering the intellectual and social structure of the field. By examining the connections, readers can identify clusters of authors who consistently publish in particular journals using similar sets of keywords, suggesting the presence of research communities or thematic niches within the broader domain of immersive STEM education. For example, certain authors may concentrate on topics such as virtual laboratories, inquiry-based learning, or simulation-based STEM learning, and they may favor specific journals that specialize in educational technology or STEM education. The density and thickness of the connecting lines can also signal the strength of association between authors, sources, and themes. Overall, Figure 4 provides a multifaceted view of how scholarly actors, publication venues, and conceptual foci interact, thereby enriching our understanding of both collaboration patterns and thematic specialization within the field.

5.3. Core Publication Sources in the Field

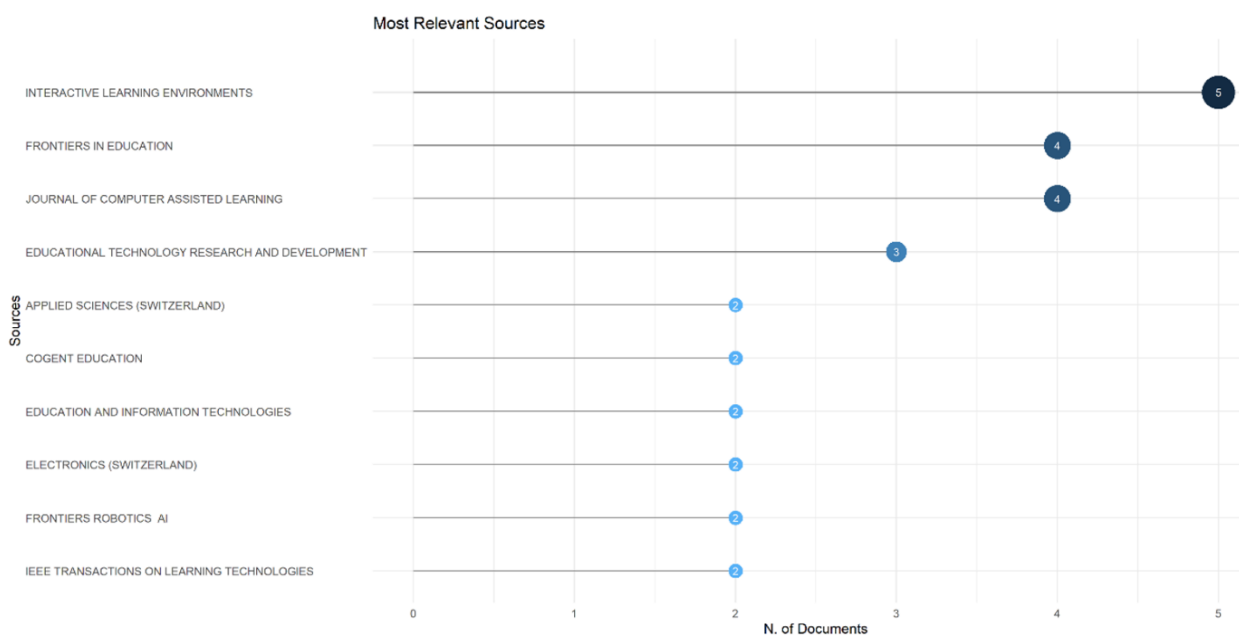

Figure 5.
Most Relevant Sources.

Figure 5 displays the most relevant sources in which research on immersive environments in STEM education is published. Usually presented as a bar chart, the figure ranks journals and conference proceedings by the number of articles they have contributed to the dataset. The sources at the top of the list can be considered core or flagship venues for this research area.

Interpreting Figure 5 enables readers to identify where the most important and sustained conversations about immersive STEM education are occurring. Journals that appear highly productive are likely to maintain a special focus on educational technology, STEM pedagogy, or digital learning environments. These venues not only shape the academic discourse but also serve as primary channels for disseminating innovative practices and empirical findings. From a practical perspective, identifying these core sources is valuable for researchers seeking appropriate outlets for their own work and for practitioners seeking to stay abreast of cutting-edge developments in immersive STEM learning. The concentration of publications in specific journals may also indicate specialized editorial policies or dedicated readerships aligned with the field’s themes, underscoring the institutional infrastructure that supports its growth.

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5.4. Geographic Distribution of Corresponding Authors

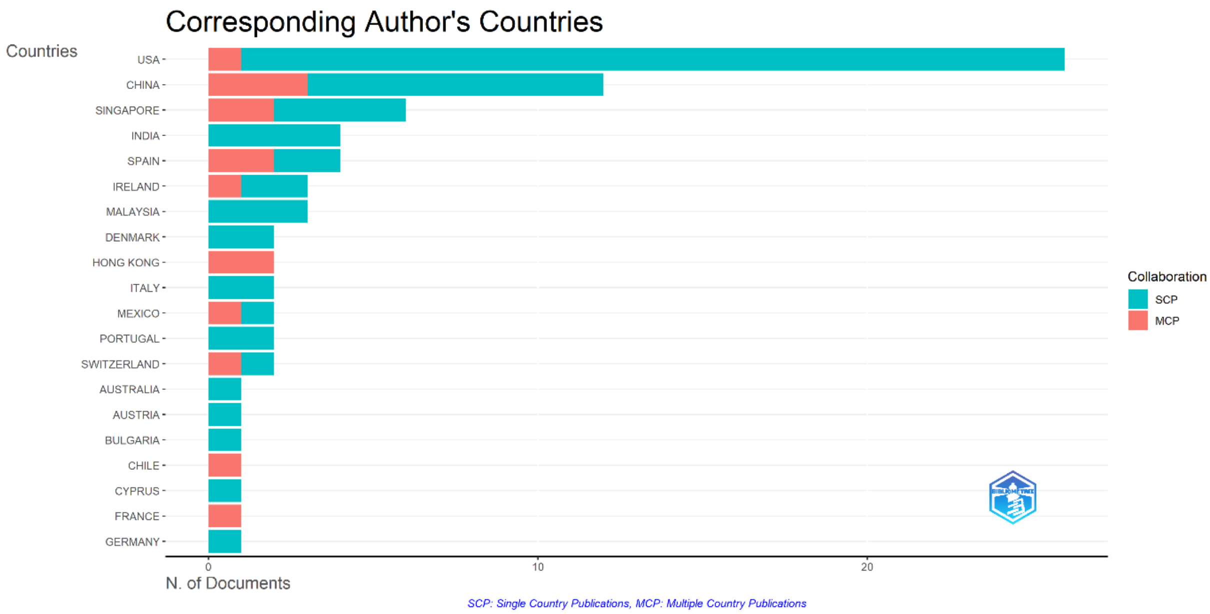

Figure 6.
Corresponding Author's Countries.

Figure 6 depicts the distribution of countries of corresponding authors, often using either a bar chart or a world map. Each country represented in the dataset is associated with the number of publications for which researchers from that country serve as corresponding authors. This visualization provides a geographical profile of scholarly leadership and initiative within the field.

The pattern observed in Figure 6 reveals which nations play prominent roles in advancing research on immersive environments in STEM education. Countries with high publication counts can be interpreted as hubs of innovation, often benefiting from strong research funding, robust digital infrastructure, and strategic priorities in STEM and educational technology. At the same time, the presence of a diverse set of countries underscores the global relevance and applicability of immersive technologies in education. It may also highlight disparities, with some regions contributing relatively few publications despite pressing needs in STEM education. These geographical insights can inspire future collaborations and knowledge transfer. For example, partnerships between high-output and low-output countries could help disseminate successful immersive learning practices more widely and support capacity building in underrepresented regions.

5.5. Global Scientific Production by Country

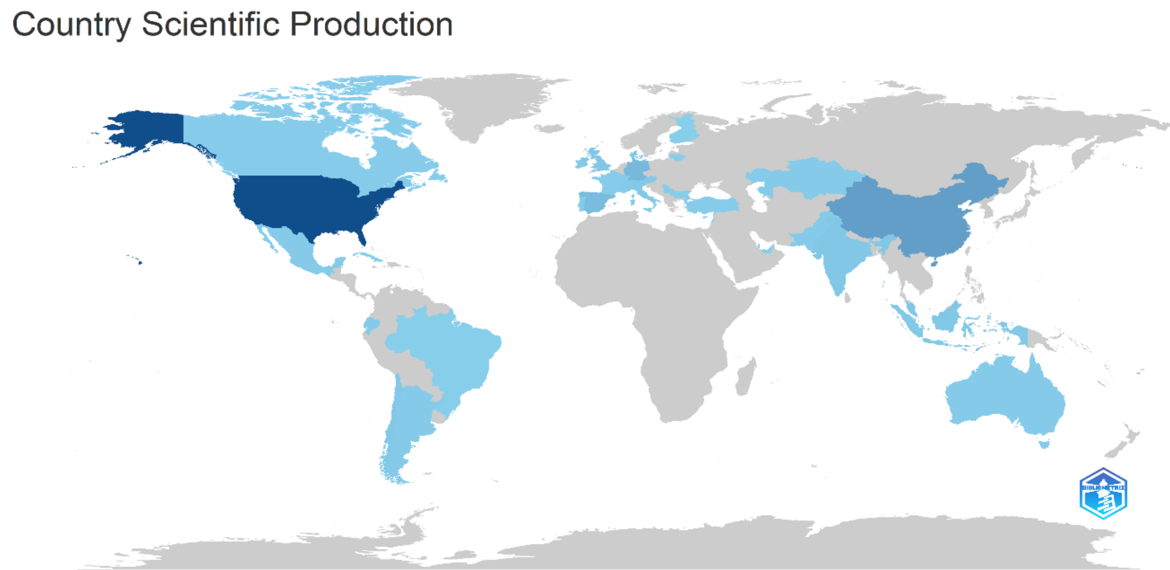

Figure 7.
Countries' Scientific Production.

Figure 7 illustrates the distribution of scientific production on immersive environments in STEM education across different countries, highlighting both leading research hubs and emerging contributors. Overall, the figure reveals a highly uneven but structured landscape: a small group of countries accounts for a substantial share of publications, a second tier of nations demonstrates consistent but moderate productivity, and a wider set of countries shows more limited yet growing engagement with the topic.

At the top of the distribution, a few countries clearly dominate the field, accounting for the largest share of publications in the dataset. These leading nations typically have well-established research ecosystems in educational technology and STEM education, strong funding schemes for digital innovation, and mature infrastructures for immersive technologies such as VR and AR. Their high publication counts suggest that immersive environments are not treated as peripheral innovations but are integrated into mainstream STEM education research agendas. In many cases, these countries also host internationally visible research groups, doctoral programs, and specialized laboratories that systematically investigate immersive learning environments. As a result, they set much of the global research agenda, define methodological standards, and frequently serve as reference points for other regions.

The second group of countries displays moderate but steady scientific production. Although their output is less extensive than that of the leading nations, they nonetheless contribute a meaningful volume of studies that collectively shape the field. These countries often present a combination of targeted research centers and collaborative projects rather than a broad national concentration of work. Their publication patterns may reflect strategic initiatives such as digital education reforms, STEM promotion policies, or university-industry partnerships that support the adoption of immersive tools in specific STEM domains (e.g., engineering, physics, or computer science). Notably, countries in this group often collaborate frequently with the top-producing nations, indicating that international partnerships play an essential role in enhancing their visibility and impact. Their contribution is therefore characterized not only by the number of studies but also by their integration into broader global networks.

Beyond the leading and intermediate tiers, Figure 7 also shows a long tail of countries with relatively low but non-negligible levels of scientific production. Although each of these countries contributes only a small number of publications, their presence is essential because it demonstrates the global relevance and diffusion of immersive STEM education research. For some of these nations, limited output may reflect emerging interest, restricted access to immersive technologies, or constraints in research funding. However, the mere appearance of these countries in the figure suggests that immersive environments are being explored across diverse educational systems and socio-economic contexts. In many cases, publications from these countries are driven by pioneering teams or individual champions who adapt immersive technologies to local needs, such as rural STEM education, resource-constrained schools, or context-specific curricula. Over time, these early efforts may evolve into larger projects and institutionalized research programs, potentially repositioning these countries into higher tiers of production.

Taken together, Figure 7 underscores three key patterns. First, the field is anchored by a small set of high-output countries that function as global leaders in immersive STEM education research. Second, a broader circle of moderately productive countries helps diversify perspectives and contexts, often through collaborative endeavors. Third, an expanding periphery of low-output but emerging contributors indicates that interest in immersive environments is spreading worldwide, even in the face of structural constraints. This stratified distribution has important implications: it suggests that while the intellectual core of the field is concentrated in specific regions, there is significant potential for capacity building, cross-border collaboration, and knowledge transfer to support less-represented countries. For educators, policymakers, and researchers, Figure 7 thus not only maps where the bulk of evidence currently comes from but also points toward regions where future investment and collaborative projects could substantially enrich the global discourse on immersive environments in STEM education.

5.6. High-Frequency Keywords in Immersive STEM Education Research

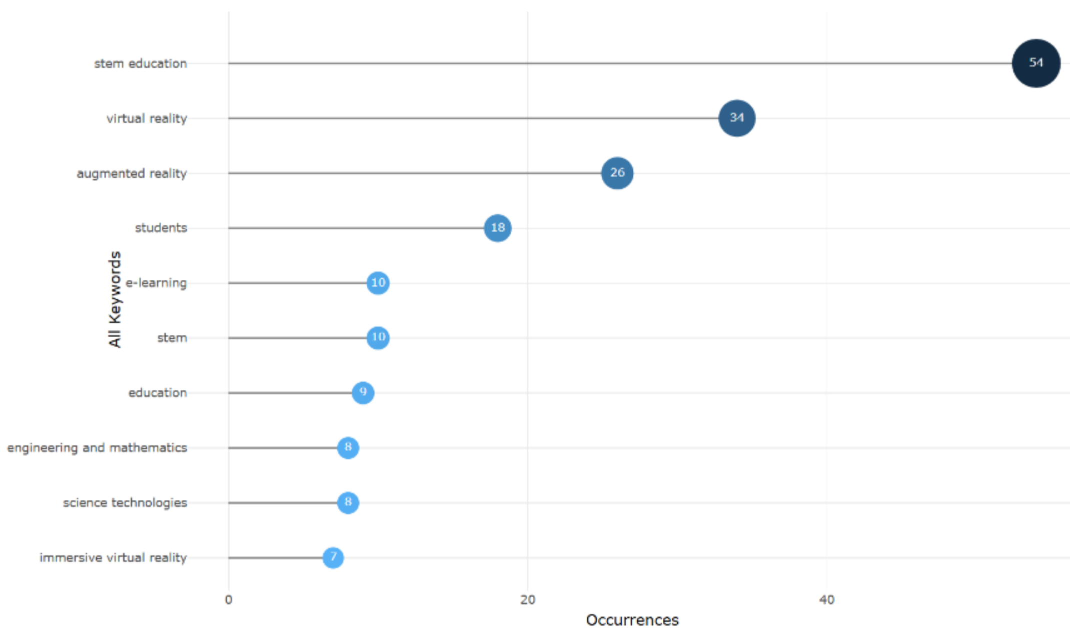

Figure 8.
Most Frequent Words.

Figure 8 illustrates the most frequent words (or author keywords) that appear across the articles in the dataset. Typically displayed as a bar chart or ranked list, this figure quantifies how often key terms related to immersive environments and STEM education are used. Common terms might include “virtual reality,” “simulation,” “STEM,” “science education,” “engineering,” “problem-based learning,” and “student engagement,” among others.

The significance of Figure 8 lies in its ability to reveal the field's conceptual core. High-frequency words can be seen as central pillars around which research questions, theoretical frameworks, and instructional designs are constructed. For example, the prominence of terms like “virtual reality” or “immersion” reflects the field's technological dimension, whereas words such as “learning outcomes,” “motivation,” or “engagement” highlight its pedagogical and psychological concerns. Moreover, examining combinations of frequent terms allows us to infer dominant research directions, for instance, studies focusing on how immersive tools influence specific STEM competencies or affect students’ motivation to learn. By quantifying conceptual emphases, Figure 8 provides a foundation for more advanced analyses, such as co-occurrence networks and thematic mapping, which explore how these concepts interrelate and evolve.

5.7. Word Cloud Representation of Dominant Terms

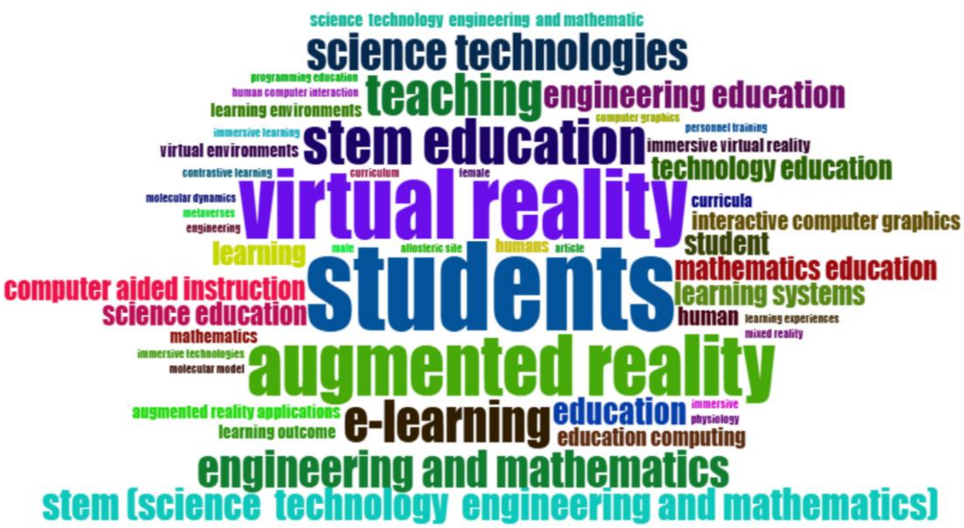

Figure 9.
Word Cloud.

Figure 9 presents a word cloud that visually represents the relative frequency of keywords or important terms in the dataset. In this visualization, the size of each word is proportional to its frequency of occurrence: larger words appear more often across the articles, while smaller words are less frequent. The word cloud thus offers a highly intuitive and accessible summary of the research field’s thematic profile.

Although less analytically precise than numerical charts, Figure 9 is particularly effective in communicating the main focus areas to a wide audience, including readers who may not specialize in bibliometric methods. By quickly scanning the word cloud, one can identify the core concepts that dominate the literature, as well as supporting themes that appear regularly but with lower prominence. The visual juxtaposition of technological terms (e.g., related to immersive devices or virtual environments) with educational terms (e.g., learning, teaching, assessment, STEM) underscores the dual nature of the field as both technologically driven and pedagogically oriented. In combination with Figure 8, the word cloud provides both a quantitative and a visual confirmation of the central concepts structuring the research landscape.

5.8. Keyword Co-occurrence Network Structure

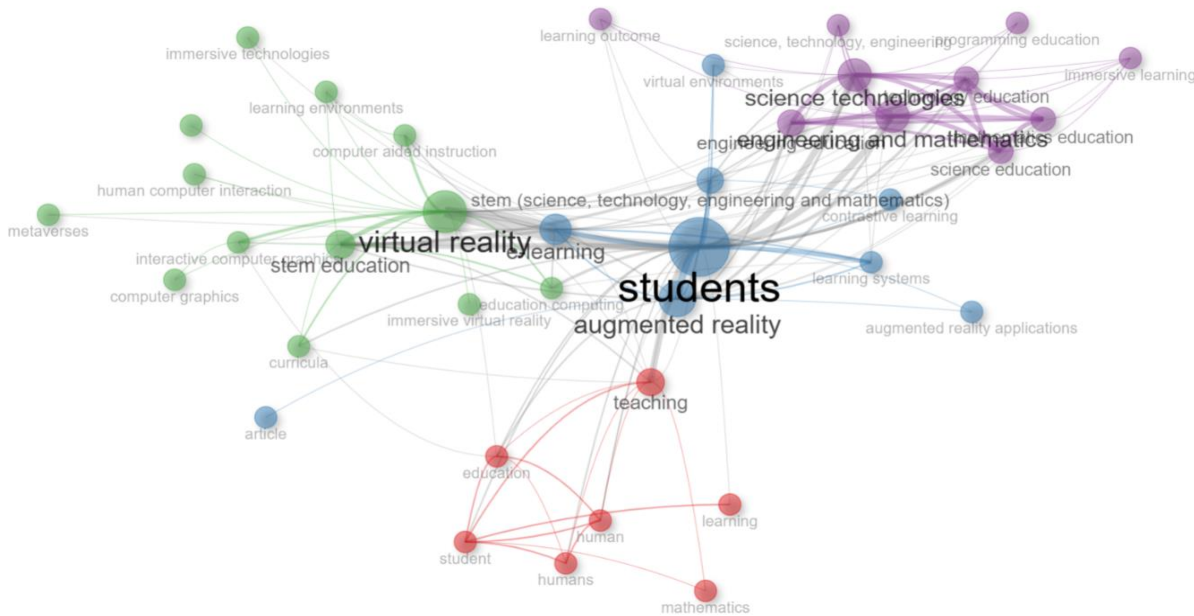

Figure 10.
Co-occurrence Network.

Figure 10 shows the co-occurrence network of keywords, mapping how frequently specific terms appear together within the same documents. In this network visualization, each node represents a keyword, and the links between nodes indicate co-occurrence relationships. The thickness or weight of the links reflects the strength of association between keywords, while the spatial arrangement often groups strongly connected terms into clusters.

This figure reveals the conceptual structure of immersive STEM education research at a deeper level than simple frequency counts. By analyzing the clusters that emerge, readers can identify distinct thematic areas, such as “virtual reality for laboratory simulations,” “game-based learning in STEM,” or “immersive environments for engineering design.” Nodes at the center of clusters or with many connections can be interpreted as pivotal concepts that integrate multiple subtopics. Conversely, peripheral nodes may represent emerging or niche themes that are not yet strongly integrated into the mainstream discourse. The co-occurrence network, therefore, provides insight into how different concepts interrelate, which themes are well-established, and where potential research gaps or opportunities for integration may exist. It also supports the subsequent interpretation of the thematic map by highlighting the underlying structure of keyword relationships.

5.9. Thematic Map of Immersive STEM Education Research

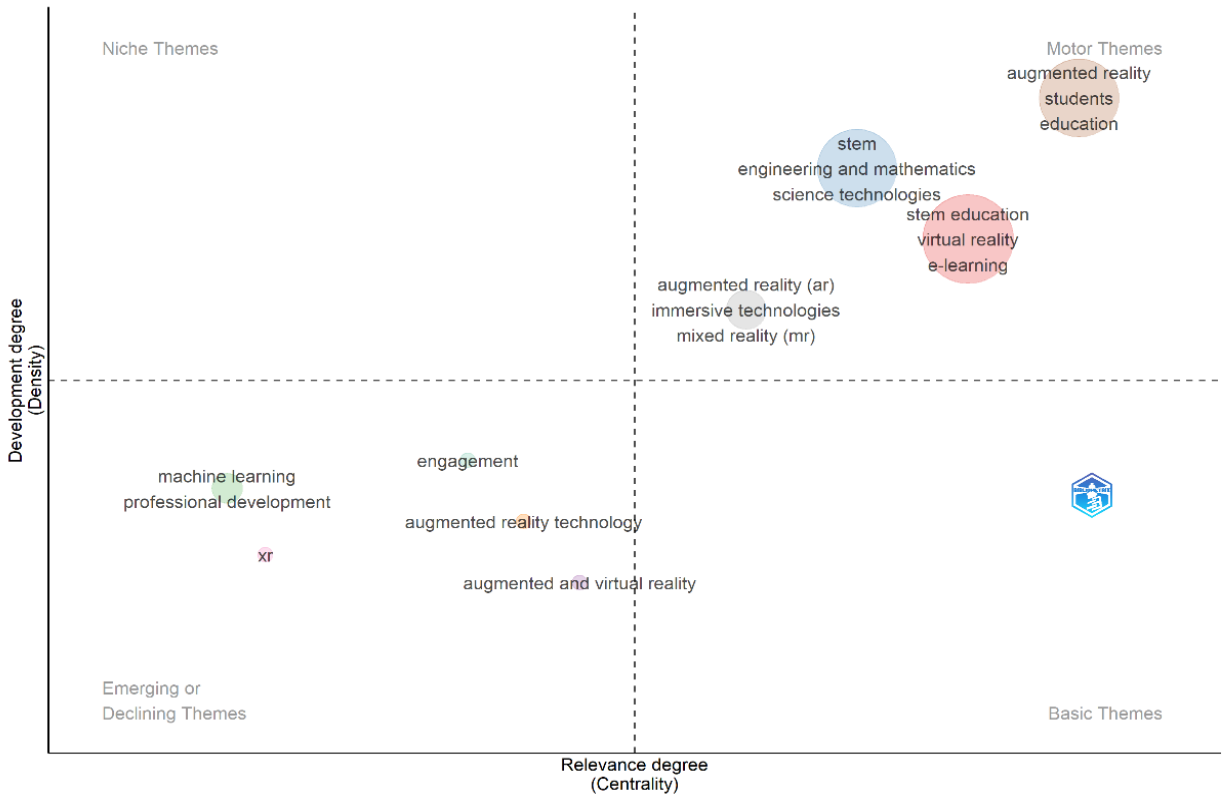

Figure 11.
Thematic Map.

The thematic map displayed in this figure organizes clusters of keywords into a two-dimensional space defined by centrality and density. Centrality reflects the degree to which a theme is connected to other themes (its importance within the overall field). At the same time, density represents the strength of internal cohesion among the keywords in that theme (its level of development). Based on these two dimensions, themes are usually categorized into four quadrants: motor themes (high density, high centrality), basic themes (low density, high centrality), emerging or declining themes (low density, low centrality), and niche or highly specialized themes (high density, low centrality). This categorization allows a comprehensive understanding of the conceptual structure of immersive STEM education research. Each cluster represents a group of closely associated keywords that frequently co-occur within the examined literature.

5.9.1. Motor Themes (High Centrality, High Density)
(Upper-Right Quadrant)

This quadrant contains themes that are both well-developed and highly relevant, functioning as the intellectual engines of the field. In the provided map, clusters such as:

- "engineering and mathematics"
- "science technologies"
- "engineering education"

Are positioned as central drivers of the domain. Their placement indicates that immersive environments, particularly VR/AR systems, are increasingly embedded in STEM disciplines that require conceptual visualization, laboratory simulations, and applied problem-solving. The high density suggests that these themes possess robust theoretical and methodological structures, supported by an active research community producing cohesive, sustained outputs. Their high centrality also shows that studies within these themes strongly influence and are influenced by other research areas in immersive STEM education.

This emphasizes that engineering and applied sciences are the dominant disciplinary homes for immersive technologies, particularly where virtual simulations replicate complex spatial, mechanical, or scientific processes.

5.9.2. Niche Themes (High Density, Low Centrality)
(*Upper-left quadrant*)

This quadrant contains themes that are highly developed but peripheral to the core of the field. In the figure, the keywords appearing here include:

- "interactive computer graphics."
- "computer graphics."
- "human–computer interaction."
- "education" (in some overlapping cases)
- "student", "human."

The high density of these clusters suggests that they form specialized areas with strong internal cohesion, often focusing on technical or usability aspects of immersive systems. However, their lower centrality implies that they are not yet structurally integrated into the main trajectory of immersive STEM education research.

These topics represent technical foundations or supporting domains, particularly the design, interaction mechanics, and human factors underlying immersive technologies. Although foundational for system development, they are less often centered in STEM-specific pedagogical investigations. Their peripheral position suggests strong potential for future integration as immersive learning designs become more sophisticated and interdisciplinary.

5.9.3. Basic Themes (High Centrality, Low Density)
(*Lower-right quadrant*)

Basic themes are important but underdeveloped, forming the conceptual backbone of the field, yet requiring further refinement. In this figure, the prominent basic themes include:

- "students"
- "virtual reality."
- "augmented reality."

This cluster is one of the most crucial on the map. Its high centrality indicates that these keywords are essential anchors across numerous publications. However, its relatively lower density shows that the theme, while broad and widely referenced, remains conceptually diffuse and insufficiently consolidated.

This configuration often appears when a field is growing rapidly, with many emerging applications but relatively fewer integrative frameworks. The positioning suggests that the central role of VR/AR for student learning is widely acknowledged, but theoretical foundations, comparative models, and standardized pedagogical frameworks are still developing. This marks an important opportunity for future research to deepen conceptual clarity and empirical rigor.

Also in this quadrant are secondary concepts such as:

- "learning"
- "curricula"
- "immersive virtual reality"

These support the notion that curriculum integration and immersive learning design are widely recognized themes but still require more systematic investigation to reach the level of motor themes.

5.9.4. Emerging or Declining Themes (Low Centrality, Low Density)
(*Lower-left quadrant*)

This quadrant contains themes that are weakly developed and weakly connected. They may represent emerging areas gaining traction or declining areas losing scholarly attention. The themes in this quadrant include:

- "learning experiences"
- "student engagement"
- "personalized training"
- "virtual reality technology"
- "media arts" (slightly overlapping)
- "metaverse" (if present in the cluster)

These keywords suggest pedagogical elements that are important for immersive learning but have not yet formed cohesive or central research areas within STEM education. Their low density indicates fragmented theoretical development, and their low centrality shows that they have not yet become structurally influential within the field.

Such themes often represent frontier or transitional topics. For example, the positioning of "metaverse technology" or "virtual reality technology" may indicate early-stage exploration where researchers test new tools but have not yet produced a large, interconnected body of work. Similarly, student engagement and learning experiences are crucial constructs in education but may not yet be extensively theorized in STEM-focused immersive learning contexts.

This quadrant can therefore be interpreted as a space of future opportunity, where studies may expand as immersive technologies become more integrated into mainstream pedagogy.

Overall Interpretation of the Thematic Structure

Figure 11 demonstrates a clear structural pattern:

- The field is currently driven by applied STEM domains (engineering, science, and technologies), indicating strong disciplinary relevance.
- VR/AR and students form the central but underdeveloped cluster, showing the field's rapid expansion and need for theory building.
- Technical design domains (HCI, computer graphics) are robust but peripheral, important foundations, but not yet central to pedagogical research.
- Emerging pedagogical concepts (student engagement, learning experiences) appear in early or diffuse stages, indicating future lines of growth.

In summary, the thematic map reveals that immersive STEM education research is a maturing field: it is conceptually anchored by VR/AR applications with strong connections to engineering education, while still developing theoretical sophistication in pedagogical and experiential learning dimensions. This map provides a strategic overview of where research is concentrated, where it is emerging, and where new theoretical and empirical contributions are most needed.

5.10. Results in Summary

The overall results of this bibliometric analysis reveal a rapidly expanding and increasingly sophisticated body of research on immersive environments in STEM education. Across all figures and analytical dimensions, a clear picture emerges: the integration of immersive technologies, particularly virtual reality (VR), augmented reality (AR), mixed reality (MR), and other forms of digital simulation, has become both a significant research trend and a foundational component of contemporary STEM learning design.

The temporal pattern in annual scientific production (Figure 3) shows consistent growth, indicating that immersive STEM education is no longer a niche interest but a steadily maturing research domain.

The upward trajectory corresponds with global advancements in VR/AR accessibility, increased institutional investment in digital transformation, and the recognition of immersive learning as a powerful tool for enhancing conceptual understanding and experiential engagement in STEM subjects. This growth suggests that immersive technologies are transitioning from experimental pedagogical enhancements to mainstream components of STEM curricula.

The structural mapping of authors, sources, and keywords (Figure 4) shows a well-defined academic ecosystem in which specific authors frequently publish in established educational technology journals while employing a consistent set of keywords related to simulation, virtual laboratories, STEM learning, and student engagement. These patterns reveal both the presence of cohesive scholarly communities and the existence of cross-disciplinary research bridges that connect technological development with pedagogical innovation. The most relevant publications (Figure 5) further emphasize that immersive STEM education is anchored in reputable, specialized journals, many of which serve as hubs for ongoing theoretical and empirical contributions.

Geographical analyses (Figures 6 and 7) highlight the global nature of immersive STEM education research. A small number of countries act as major contributors, reflecting strong research funding and technological infrastructure. However, the broader distribution of contributing countries, both corresponding authors and publication outputs, indicates that immersive technologies are being explored in diverse educational contexts worldwide. This international spread underscores the adaptability of VR/AR tools across varying levels of educational development and suggests that the field benefits from cross-cultural perspectives, collaborative networks, and shared innovation agendas.

The conceptual profile of the field is illuminated through the analysis of high-frequency keywords (Figure 8) and the visual word cloud (Figure 9), both of which reveal a strong focus on immersive technologies, learning processes, and STEM-specific concepts. Dominant terms such as "virtual reality," "learning," "STEM," and "students" point to technology-enhanced learning as the core intersectional theme. These terms also reflect dual priorities in the literature: (1) advancing the technical design and functionality of immersive tools, and (2) examining their impact on student learning outcomes, engagement, and experiential understanding.

The network and thematic analyses (Figures 10 and 11) provide deeper insights into the field's intellectual structure. The co-occurrence network shows how research topics cluster into conceptual communities, such as virtual laboratory simulations, interactive learning environments, engineering education, and science technologies, revealing the multidimensionality of immersive STEM research. The thematic map further categorizes these clusters into motor, basic, niche, and emerging themes. Motor themes, such as engineering education and science technologies, drive the field's development, while basic themes, particularly the central roles of virtual and augmented reality and of students, form the foundational conceptual scaffold. Niche themes focus on specialized technical aspects, whereas emerging or declining themes reflect areas of experimentation, such as student engagement, personalized training, or metaverse-related concepts.

Taken together, the results indicate that immersive environments have become a critical innovation in STEM education research. The field shows clear evidence of expansion, conceptual diversification, and cross-disciplinary integration. It is simultaneously technology-driven and pedagogy-oriented, with strong theoretical underpinnings emerging alongside frequent applied studies. The diverse themes, global participation, and stable publication growth all demonstrate that immersive STEM education is not only an established scholarly field but also has substantial potential for future innovation, particularly in areas such as student-centered learning, curriculum integration, and advanced immersive technologies.

Overall, this bibliometric analysis reveals a robust, evolving, and globally distributed research landscape characterized by strong growth momentum, rich conceptual structure, and increasing scholarly attention to the transformative role of immersive environments in STEM teaching and learning.

6. Discussion

The findings of this bibliometric analysis demonstrate that research on immersive environments in STEM education has expanded rapidly in recent years, reflecting the broader global shift toward digital and experiential learning technologies. Annual scientific production has consistently increased, indicating sustained scholarly interest driven by improved VR/AR/MR accessibility and their proven ability to enhance STEM learning experiences [1, 2, 6, 8]. This growth aligns with evidence showing that immersive platforms promote deeper engagement, agency, identity formation, and representational flexibility among learners across diverse STEM contexts [1, 7, 8, 14].

The intellectual mapping results reveal that strong research communities anchor the field focused on VR laboratories, simulation-based STEM learning, mixed-reality visualization, and engineering education [2, 6, 12, 17]. These clusters correspond to well-established findings that immersive environments support complex practical skills, conceptual understanding, and procedural training, particularly in engineering, biomedical, and computational domains [12, 13, 17, 20]. High-frequency keywords such as *virtual reality*, *STEM*, *simulation*, and *learning* confirm the centrality of these themes.

Geographically, contributions remain concentrated in technologically advanced countries, reflecting disparities in access to immersive equipment and research infrastructure [3, 4, 16]. Nevertheless, growing participation from diverse regions suggests increasing global adoption of immersive STEM applications, including in language-integrated STEM learning, cultural STEM collaborations, and digital literacy programs [4, 9, 21].

The thematic map further illustrates that while simulation-driven engineering and science technologies function as motor themes, foundational areas such as VR/AR for student learning remain conceptually broad and underdeveloped, indicating a need for more robust theory-building and standardized pedagogical models [6, 8, 19]. Emerging themes, including personalized immersive training and early metaverse applications, highlight future opportunities for innovation but require more empirical work to establish their educational value [10, 11, 22].

Overall, the results depict a maturing field characterized by strong growth, deepening specialization, and expanding global relevance. However, challenges remain regarding theoretical integration, equitable access, and empirical validation of emerging immersive technologies. Addressing these gaps will be essential for maximizing the long-term impact of immersive environments on STEM education.

7. Limitations

This bibliometric analysis has several limitations that should be acknowledged. First, the study relied exclusively on the Scopus database, which, although comprehensive, may exclude relevant publications indexed in other databases such as Web of Science, ERIC, Dimensions, or IEEE Xplore. This may result in partial coverage of emerging or interdisciplinary research on immersive environments in STEM education. Second, the analysis is constrained by metadata quality; variations in author names, keyword labeling, institutional affiliations, and incomplete records may influence network structures and thematic classifications despite the data-cleaning procedures applied.

Third, bibliometric methods emphasize quantitative patterns such as publication counts, citations, and keyword co-occurrence but do not assess the pedagogical quality, instructional design rigor, or empirical validity of immersive STEM studies. As a result, high citation counts may not directly reflect educational effectiveness or methodological rigor. Fourth, the cross-sectional nature of the dataset limits the ability to capture real-time shifts in research trajectories, especially considering the rapid evolution of VR/AR/MR technologies and emerging platforms such as metaverse-based learning environments.

Finally, language restrictions on English-only publications may inadvertently exclude culturally relevant immersive STEM research from non-English-speaking regions. This limitation affects the global representativeness of scientific production and may understate contributions from countries developing localized immersive learning frameworks.

8. Conclusion

This bibliometric analysis provides a comprehensive overview of the global research landscape on immersive environments in STEM education, revealing a rapidly expanding and increasingly sophisticated field. The steady rise in annual scientific production reflects growing recognition of VR, AR, MR, and XR as transformative tools that enhance engagement, conceptual understanding, and experiential learning in STEM contexts. The structural and conceptual analyses highlight well-established research clusters related to engineering education, simulation-based learning, and virtual laboratories, demonstrating that immersive technologies have become central to supporting complex cognitive and procedural skills.

The thematic map indicates that while certain areas, such as simulation-driven engineering and science technologies, serve as motor themes, foundational domains involving VR/AR for student learning require further theoretical refinement. Emerging themes, including personalized immersive training and early-stage metaverse applications, represent promising avenues for future inquiry but currently lack substantial empirical grounding. Global participation remains uneven, with contributions concentrated in technologically advanced countries, though an encouraging increase in international diversity is evident.

Overall, the findings illustrate that immersive environments have transitioned from experimental innovations to influential pedagogical tools within STEM education. To sustain this momentum, future research should prioritize theoretical integration, methodological rigor, and equitable access to immersive technologies. Strengthening these areas will support the development of immersive learning ecosystems that can meaningfully enhance STEM teaching, learning, and learner experience on a global scale.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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