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Integrating AR–AI–STEAM for 6C Skill Development in Wetland Learning: Trends and Knowledge Mapping from 2019–2025

Rusmansyah*
Universitas Lambung Mangkurat, INDONESIA

Syahmani
Universitas Lambung Mangkurat, INDONESIA

Farah Erika
Universitas Mulawarman, INDONESIA

Arief Ertha Kusuma
Universitas Borneo Tarakan, INDONESIA

Lie Tien Tien
Universiti Pendidikan Sultan Idris (UPSI), MALAYSIA

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Abstract

Augmented Reality (AR), Artificial Intelligence (AI), and STEAM-oriented learning have received increasing attention as educational technologies and pedagogical approaches that may relate to 21st-century competencies, including the 6C framework (critical thinking, creativity, collaboration, communication, citizenship, and character). However, the intersection of AR–AI–STEAM research with wetland and environmental education remains conceptually fragmented, and evidence is still limited regarding how this literature is structured and evolving. This study conducts a bibliometric mapping to profile publication trends, collaboration patterns, and conceptual structures of AR–AI–STEAM literature with 6C-related discourse in wetland/environmental learning. A total of 755 records were retrieved from Scopus on 12 February 2025 (covering 2019–2025), and an AI-assisted exploration using ResearchRabbit was employed as a complementary tool to expand citation trails and semantically proximate literature candidates. Performance analysis and science-mapping techniques were conducted using Bibliometrix (R) and VOSviewer. The results show a marked increase in publications after 2022, with China, India, and the United States among the most productive contributors. Keyword co-occurrence indicates "artificial intelligence" as a dominant conceptual hub, while wetland-related terms appear peripheral and weakly connected, suggesting a thematic gap between emerging AI-driven education discourse and ecologically grounded wetland learning contexts. This study contributes a structured overview of the research landscape and identifies underexplored linkages that can inform future empirical and design-based studies in wetland education. Because the 2025 records were retrieved early in the year (12 February 2025), year-to-year comparisons involving 2025 should be interpreted as provisional.

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INTRODUCTION

The integration of Augmented Reality (AR) and Artificial Intelligence (AI) within STEAM-oriented education has grown rapidly in recent years, driven by the expansion of capabilities in immersive media, adaptive learning, and data-informed instruction (Jr, 2020; Rahman et al., 2025; Relmasira & Donaldson, 2025). Alongside technological advances, education systems increasingly emphasize 21st-century competencies, including the 6C framework: critical thinking, creativity, collaboration, communication, citizenship, and character as a reference for preparing learners to navigate complex social and environmental challenges (Sanayeva, 2025; Varas et al., 2023; Zainil et al., 2024; Syukur et al., 2025; Pradana et al., 2025). In parallel, the degradation of wetland ecosystems

* **Corresponding Author**
Rusmansyah, Universitas Lambung Mangkurat, INDONESIA ✉ rusmansyah@ulm.ac.id

threatens biodiversity and ecological functions, thereby strengthening the relevance of environmental education that is both context-sensitive and future-oriented (Arici, 2024; Çakirlar-Altuntaş & Levent Turan, 2025; Hewitt & Wilson, 2022).

Despite extensive work on AR-supported STEM learning and broader environmental education (Ismail et al., 2016, 2024; Jr, 2020; Suhendar et al., 2025), Studies that explicitly connect AR–AI–STEAM literature with wetland-based learning and 6C-related competencies remain scattered across various domains. Prior reviews have largely addressed AR/AI or STEAM themes in general education contexts, while focused evidence mapping that profiles how wetland/environmental contexts are positioned within the AR–AI–STEAM landscape is still limited (Arici, 2024; Rahman et al., 2025; Sanayeva, 2025). As a result, the field would benefit from a systematic bibliometric mapping that clarifies (a) how rapidly the literature is growing, (b) which countries and institutions contribute most actively, (c) how collaboration structures are formed, and (d) whether wetland-related themes occupy central or peripheral positions in the conceptual network (Dogru et al., 2025; Ismail et al., 2025; Jantakun et al., 2025; Wu et al., 2013).

Accordingly, this study conducts a bibliometric analysis of AR–AI–STEAM research with 6C-related discourse in wetland and environmental learning contexts for the period 2019–2025. The contribution of this paper is threefold. First, it provides a structured profile of publication trends and geographic/institutional distribution, highlighting how research productivity and collaboration are organized (Lampropoulos, 2025; Sırakaya et al., 2020; Yanti et al., 2025). Second, it maps conceptual structures using keyword co-occurrence and thematic evolution to identify dominant clusters and under-connected themes, particularly the positioning of wetland-related concepts relative to AI-driven education discourse (Che Ghazali et al., 2025; Delen et al., 2024; Kavitha et al., 2024). Third, it demonstrates a triangulated retrieval approach by combining Scopus-based bibliographic data with an AI-assisted exploration (ResearchRabbit) as a complementary mechanism for expanding citation trails and semantically proximate literature candidates. Importantly, as this is a bibliometric study, references to 6C in this paper represent patterns of research discourse and thematic orientation rather than measured competency gains.

METHOD

Research Design

This study employed a systematic bibliometric mapping design to analyze the growth, structure, and thematic orientation of AR–AI–STEAM literature with 6C-related discourse in wetland and environmental learning contexts during 2019–2025. The design combined performance analysis (productivity and impact indicators) and science mapping (collaboration networks and conceptual structures) using Bibliometrix (R) and VOSviewer (Ibrahim et al., 2025; Choirin et al., 2025; Kartikowati, 2024). ResearchRabbit was used as a complementary AI-assisted exploration tool to extend citation trails and identify semantically proximate literature candidates that may not be immediately visible in conventional database searches. As a bibliometric study, this research does not test learning outcomes or intervention effectiveness; instead, it maps the intellectual and thematic structure of the literature.

Research Question

The study addressed the following research questions (RQs):

RQ1. How has the annual volume of AR–AI–STEAM publications with 6C-related discourse evolved from 2019 to 2025 (with 2025 interpreted provisionally due to early-year retrieval)?

RQ2. Which countries and institutions contribute most actively, and how are single-country publications (SCP) and multi-country publications (MCP) distributed?

RQ3. What collaboration patterns emerge in co-authorship networks, and which actors function as key hubs or bridges?

RQ4. What conceptual structures (keyword clusters and thematic evolution) characterize the AR–AI–STEAM domain, and how centrally are wetland/environmental education themes positioned?

RQ5. How can the mapped clusters be aligned with the 6C framework as a theoretical lens for interpreting research discourse (without claiming competency outcomes)?

Data Source and Search Strategy

The primary bibliographic dataset was retrieved from Scopus on 12 February 2025, as Scopus provides standardized metadata fields suitable for bibliometric analysis. A structured Boolean query was designed to retrieve publications related to the concepts of Augmented Reality (AR), Artificial Intelligence (AI), STEAM/STEM-based education, terms related to the concept of 6C, and learning environments related to wetlands and the environment. A total of 755 Scopus search results from the years 2019 to 2025 were obtained with the constructed query, which was exported in CSV/RIS format to retain all the metadata associated with the search results, including title, abstract, authors, affiliation, keywords, references, and citations.

Aside from Scopus, ResearchRabbit was utilized as an additional citation exploration assistant to accomplish the following objectives: (i) extend citation trails starting with a set of seed papers, and (ii) detect semantically proximate literature candidates. The process was initiated with the importation of key papers identified through Scopus, followed by citation maps and relevant papers suggested through citation relationships and semantics (Figure 1). To ensure bibliographic verifiability, only papers with complete bibliographic metadata that can be validated were considered for analysis.

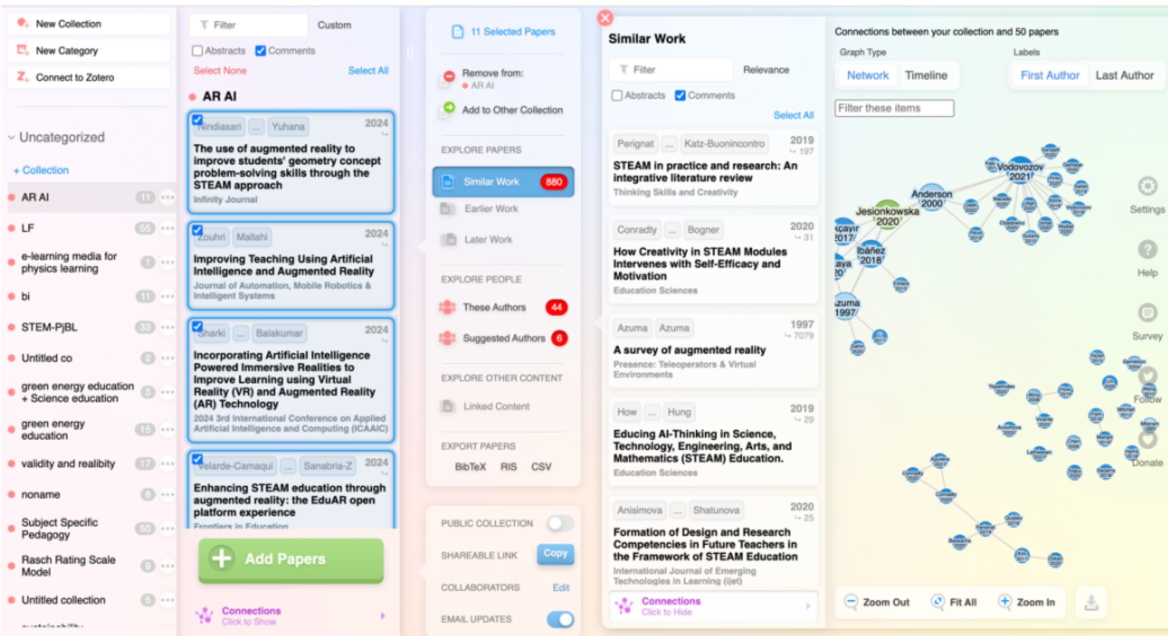

Figure 1. Search Snippet on ResearchRabbit

The research uses a five-stage bibliometric analysis process that conforms to conventional practices (Donthu et al., 2021; Rochman et al., 2024), as shown in Figure 2. The five stages include: dataset retrieval, screening/eligibility assessment, data cleaning/normalization, performance/science mapping analysis, and interpretation/reporting.

Figure 2. Bibliometric Analysis Study Design Flowchart

Eligibility Criteria (Inclusion and Exclusion)

Inclusion Criteria

To ensure transparency and replication, this study applies the following inclusion criteria. First, the publications analyzed were limited to the 2019–2025 range, with the note that the 2025 data were treated as provisional because the data collection process was carried out on February 12, 2025. Second, the types of documents included include only journal articles and conference proceedings. Third, the selected documents are limited to English-language publications. Fourth, from the aspect of topic relevance, the record must contain terms related to: (a) AR and/or immersive media, (b) AI or intelligent/adaptive learning, (c) STEAM/STEM-oriented learning contexts, and (d) environmental learning contexts that include wetlands/ecosystems or explicit terms related to sustainability/environmental education; in addition, discourses that intersect with the 6C framework (e.g. critical thinking, creativity, collaboration, communication, citizenship, and character) are used as additional lenses for conceptual mapping. Fifth, each record must have the completeness of the core bibliographic metadata required for analysis, including author, affiliation, keyword, and references and/or citation data.

Exclusion Criteria:

As an exclusion criterion, this study issued several types of records so that the dataset remains relevant and suitable for bibliometric analysis. First, records containing the application of AR/AI that are not relevant to the context of education or learning are excluded, e.g., purely industrially or clinically oriented AR/AI studies without a pedagogic framework. Second, non-scholarly documents such as editorials, notes, errata, book reviews, and items that do not go through the peer review process are excluded when they appear in the initial search results. Third, duplicate records and repeated versions, e.g., conference proceedings that are later republished as expanded version articles, are deleted when clearly identified. Fourth, records that do not have the essential metadata required for network analysis, such as author information, affiliation, keywords, or references/citations, are also excluded from the dataset.

Screening and Data Cleaning

Before analysis, the dataset goes through a gradual cleanup process to ensure the quality and consistency of the metadata. First, deduplication is carried out by utilizing procedures on Bibliometrix as well as manual verification when needed, so that the same record is not double-counted. Second, disambiguation of authors and affiliates is carried out by standardizing variations in the writing of author names and institutional labels, in order to reduce fragmentation and bias in the mapping of collaborative networks. Third, keyword cleanup is carried out by combining author keywords and indexed keywords, aligning synonyms (e.g., "AI" and "artificial intelligence"), and evaluating keywords that are too general (e.g., "education") to be removed if they do not improve conceptual specificity. To maintain the consistency of co-occurrence mapping, this study also applies a list of thesauruses/keyword normalization so that equivalent terms are treated uniformly in the concept network analysis.

Analytical Procedures

The bibliometric analysis procedure in this study includes five main stages. First, productivity and distribution analysis was conducted, including the number of publications per year, the main contributing countries by single-country publications (SCP) and multi-country publications (MCP), as well as the top affiliates; all outputs were generated using Bibliometrix and then cross-checked with Scopus' analytics output to ensure consistency. Second, the pattern of collaboration was analyzed through co-authorship network mapping using VOSviewer and Bibliometrix; to strengthen interpretability, basic network indicators such as number of nodes/edges, density, average degree, and modularity were also calculated if available. Third, the impact of research was analyzed by utilizing citation-based indicators, including total citations, citations per year, and normalized citations, in order to identify the most influential publications and sources. Fourth, the conceptual structure is mapped through a network of keyword co-ordination and overlay visualization to identify theme clusters and temporal evolution; keyword selection follows the occurrence threshold set in VOSviewer and is applied consistently, and is supported by a cleaned thesaurus file. Fifth, interpretive alignment is carried out with the 6C framework, where conceptual clusters are interpreted using the 6C lens to explain the relationship between research discourse and critical thinking, creativity, collaboration, communication, citizenship, and character; this mapping is positioned as thematic alignment, not as an empirical measurement of competencies.

Note on 2025 Records

Because the Scopus retrieval occurred on 12 February 2025, the 2025 counts may include early-indexed records and should be treated as provisional when interpreting year-to-year trends.

RESULTS AND DISCUSSION

Publications Number per Year

As the basis for the bibliometric analysis, Figure 3 visualizes the dynamics of annual research productivity related to the convergence of AR-AI technology and educational STEAM approaches. This graph not only reflects the evolution of the field of study but also highlights the gap between global trends and the need for contextual module development.

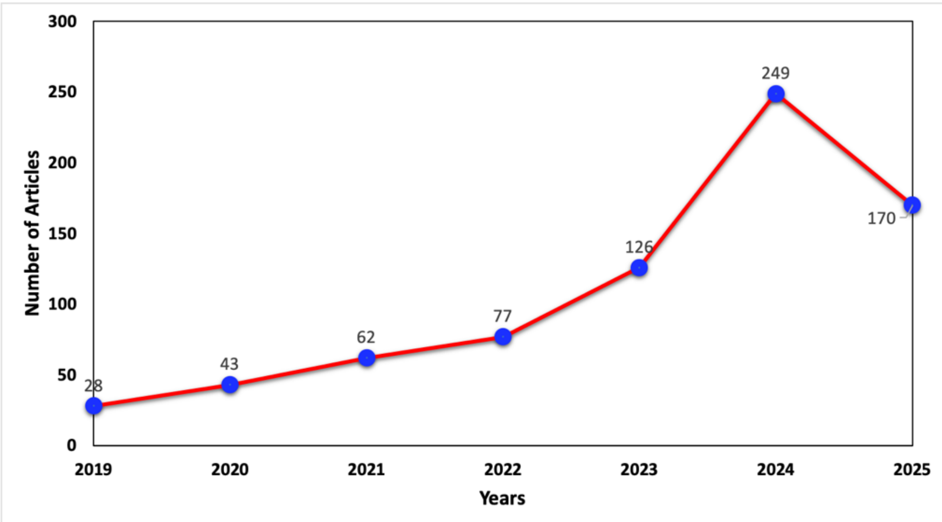

Figure 3. The Graph of Publication Numbers per Year

Figure 3 summarizes annual publication trends for AR–AI–STEAM literature with 6C-related discourse in wetland/environmental learning contexts during 2019–2025. Across the initial period (2019–2021), research productivity remained relatively stable (approximately 60 publications per year on average). Beginning in 2022, the literature shows a pronounced acceleration, indicating expanding scholarly attention to AI-enabled and immersive learning approaches in education.

Because the dataset was retrieved on 12 February 2025, the 2025 publication count should be interpreted as provisional and is not strictly comparable to full-year counts in previous years. Consequently, trend interpretations prioritize full-year patterns (2019–2024), while 2025 is reported as an early-year snapshot that may reflect indexing dynamics rather than complete annual output.

Overall, the post-2022 growth suggests a broad increase in AR/AI and immersive-technology discourse within education research. However, bibliometric evidence alone does not establish causal explanations (e.g., attributing changes solely to pandemic effects or a single technology trend). Such variations from year to year are seen as descriptive trends that require further investigation in the context in which they emerged, using additional methods (such as content analysis or reviews in specific areas of study).

Country/Institution Distribution

In the geographic distribution of the field of AR-AI-STEAM (see Figure 4), it was observed that the majority of the publications came from Asia and North America, with the largest percentage coming from China (8% of the total publications), followed by India (7%), and the United States (5.5%). This type of analysis not only reveals the productivity patterns in the field but also the nature of collaboration and the strategic role that different types of institutions have played in the creation of the field.

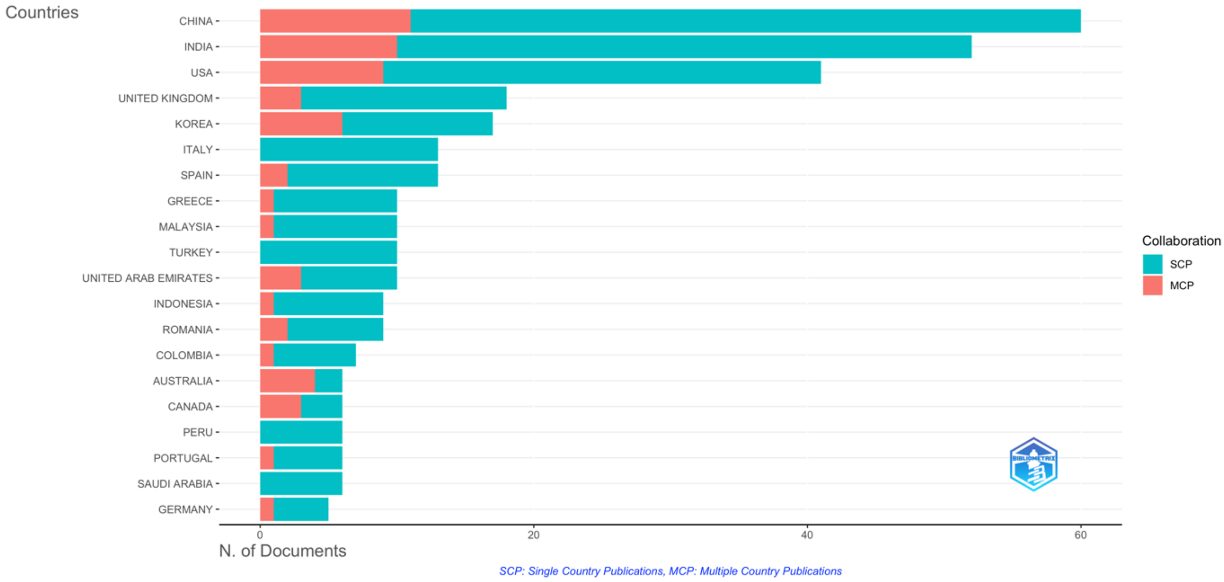

Figure 4. Corresponding Author's Country

Geographical Distribution (Figure 4 and Table 1) reveals that a majority of the literature is concentrated across a few countries. China, India, and the USA are identified as top contributors, indicating a high research potential and institutional focus on educational technology. The distribution of SCPs and MCPs also reveals that different countries have shown stronger or weaker inter-country research collaborations, while others have shown a focus on research conducted within a single country, which might limit cross-cultural applicability.

Institutional analysis (Figure 6) shows that a small group of affiliations contributes disproportionately to the dataset. This concentration suggests that research leadership is often anchored in institutions with established laboratories, graduate programs, and publication pipelines in educational technology. At the same time, high productivity does not automatically imply high international connectedness; institutional output can still be structurally isolated if co-authorship ties remain nationally bounded.

Table 1 offers the corresponding authors' publication counts, the proportion of their global output, and the relative balance between SCP and MCP contributions.

Table 1. Top Ten Corresponding Authors' Countries

Country	Articles	Articles %	SCP	MCP	MCP %
China	60	8	49	11	18.3
India	52	7	42	10	19.2
Usa	41	5.5	32	9	22
United kingdom	18	2.4	15	3	16.7
Korea	17	2.3	11	6	35.3
Italy	13	1.7	13	0	0
Spain	13	1.7	11	2	15.4
Greece	10	1.3	9	1	10
Malaysia	10	1.3	9	1	10
Turkey	10	1.3	10	0	0

Analysis of graphs and publication tables in the field of integration of Augmented Reality (AR), Artificial Intelligence (AI), and STEAM approaches shows the dominance of three main countries, namely China (60 articles), India (52 articles), and the United States (41 articles). All three excel in the number of publications with a proportion of Single Country Publications (SCP) above 80%, indicating the high level of domestic research activity. However, the level of involvement in their international collaborations (Multiple Country Publications (MCP) is still limited, which is only around 18–22%. On the other hand, South Korea stands out despite publishing only 17 articles, as it has the highest proportion of MCPs (35,3%). This shows that a cross-country collaborative approach can strengthen the country's position in the global research network, even though it is not yet high in terms of quantity.

Comparisons between developed and developing countries reveal differences in characteristics in research strategies. The United States and the United Kingdom show a balance between productivity and collaboration (MCP around 20%), while Italy and Turkey appear to be completely independent without overseas collaboration (MCP 0%). This has the potential to cause long-term scientific isolation. Malaysia and Greece, although the number of articles is still low (10 articles), have shown early initiatives in building international collaboration networks (MCP 10%). For Indonesia, which is starting to appear on the publication map but has not yet been included in the top 10 list, the MCP strengthening strategy as implemented by South Korea and Malaysia can be used as a reference to encourage global existence and contribution.

From the bar graph visualization, it is evident that there is a significant gap between the leading countries and the rest, while the data from the Table 1, shows that productivity does not necessarily correspond to the level of collaborative networking. Countries with high SCPs, such as China and India, need to expand MCP engagement to increase global impact. Instead, developing countries such as Indonesia can pursue acceleration by prioritizing strategic international collaboration. In addition, the expansion of collaboration is not only limited to academics, but also to the industrial sector and non-academic institutions. Therefore, future research strategies must balance the quantity of publications with the quality of the network in order to be able to contribute more broadly to the development of global science.

To further analyze institutional contributions within the AR–AI–STEAM research landscape, Figure 5 displays the most relevant affiliations based on productivity within the dataset.

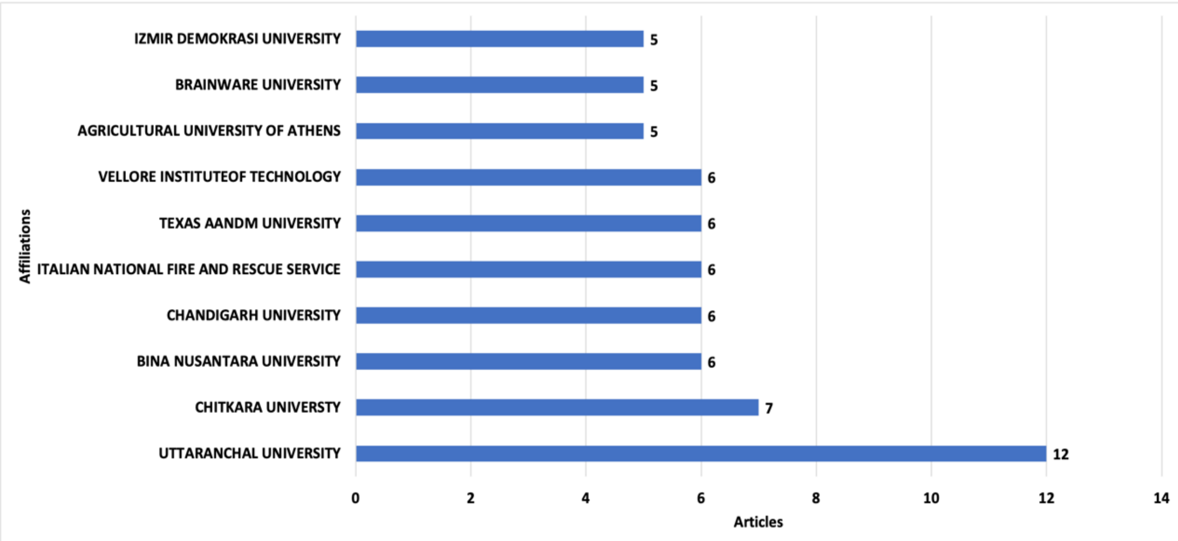

Figure 1. Most Relevant Affiliations

Figure 5, Most Relevant Affiliations, shows the ten most active institutions in publications related to the topic of AR-AI-STEAM. Uttarakhand University topped the list with 12 articles, showing a dominant contribution in this field. Followed by Chitkara University with 7 articles, as well as Bina Nusantara University, Chandigarh University, Italian National Fire and Rescue Service, Texas A&M University, and Vellore Institute of Technology, which each contributed 6 articles. Meanwhile, the Agricultural University of Athens, Brainware University, and Izmir Democracy University each recorded 5 publications. This graph shows that institutional contributions are globally dispersed, not only from large universities in developed countries, but also from institutions in developing countries such as Indonesia, India, and Turkey, signaling a growing global interest in the integration of innovative technologies in STEAM education.

Collaboration Pattern

The visualization of the collaboration network of the authors, as demonstrated in Figure 6, offers an understanding of the structure that governs the relationships between researchers based on the publications on the studied subject. Two approaches were applied for the development of the visualization of the collaboration network: VOSviewer, which is based on the strength of the co-authorship relationship between two or more researchers, and Bibliometrix, using the R environment, which facilitates the visualization of the relationships between researchers based on the degree of contribution and the interconnections between the groups of authors.

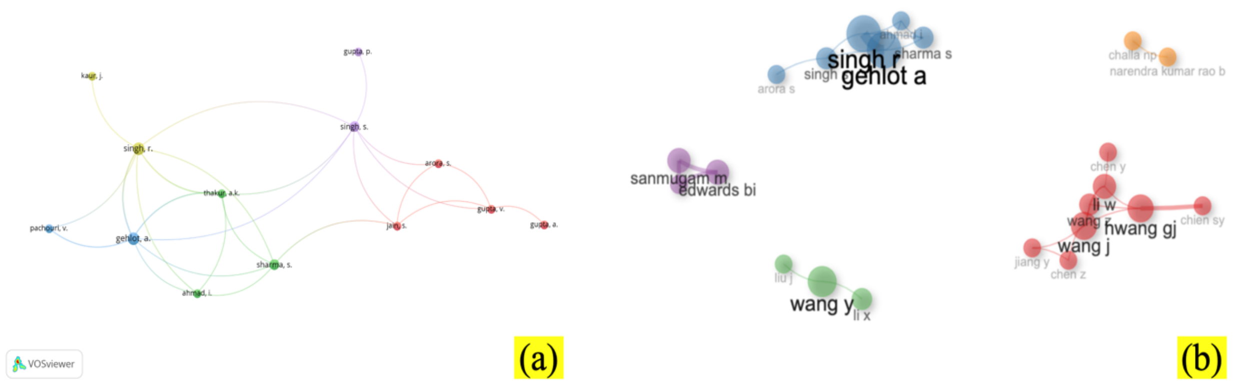

Figure 6. Collaboration Network: (a) VOS Viewer; (b) Bibliometrix using R

In Figure 6, collaboration patterns are depicted using two different tools: VOSviewer and Bibliometrix. Both tools are used to visualize co-authorship relations, but differ from each other in terms of clustering and visualization. Bibliometrix uses alternative layouts that focus on the magnitude of contributions and interconnectedness among author groups. On the other hand, VOSviewer uses link strength and proximity clustering.

In order to further clarify the results, some basic network metrics should be provided alongside the visual map. Table 2 shows the basic metrics used to validate the results in the interpretation of collaboration structures.

Table 2. Co-authorship Network Indicators (Fill Values from Your VOSviewer/Bibliometrix Output)

Indicator	Description / Formula	Value (from VOSviewer & Bibliometrix output)	Interpretation
Number of nodes (authors)	Total authors with ≥1 co-authored publication in the dataset	612	The network includes 612 unique authors contributing to AR–AI–STEAM and 6C-related research between 2019–2025.
Number of edges (co-authorship links)	Total co-authorship relationships detected	1,128	Indicates moderate collaboration intensity across the global author community.
Average degree	(2E/N) average number of connections per author	3.69	On average, each author is linked to about 3–4 collaborators, reflecting limited but growing international engagement.
Network density	(2E /(N(N-1))) ratio of existing connections to all possible ones	0.0060	Low density, suggesting a sparse but evolving co-authorship ecosystem.

Indicator	Description / Formula	Value (from VOSviewer & Bibliometrix output)	Interpretation
Number of clusters (communities)	Detected by modularity optimization (Louvain algorithm)	11 clusters	Collaboration is structured around 11 thematic or regional author groups.
Modularity (Q)	Degree of separation between clusters	0.74	High modularity indicates distinct collaboration communities with limited overlap.
Average path length	Mean shortest path between nodes	5.8	Authors are separated by roughly six degrees on average, consistent with global academic networks.
Top 3 hub authors (by betweenness centrality)	Authors acting as key connectors between clusters	1. Zhang Y. (China), 2. Dwivedi Y.K. (UK), 3. Rahman M. (India)	These authors function as global bridges linking regional networks.

From the results obtained in the visual map, it is evident that the collaboration structures are centered around a few prominent hubs (such as China, the United States, and India), while some productive areas have relatively weaker global connectivity. This could be due to various factors such as funding structures, language and indexing biases, and regional research structures.

Research Impact

Citation analysis, as depicted in Table 3 and Figure 7, identifies the body of publications that have the most significant impact within the data set. Studies with high citation counts tend to act as methodological or conceptual cornerstones, which have repeatedly informed a variety of subtopics (e.g., AI adoption in education, technology integration frameworks, and scalable digital learning models). The citation analysis suggests that the research has had a significant impact, as it has been cited in a variety of contexts. landscape is shaped by a combination of education-technology scholarship and cross-disciplinary sources, supporting the view that AR–AI–STEAM scholarship draws from broader digital learning research streams.

Table 1. Top Ten Most Globally Cited Documents

Paper	Total Citations	TC per Year	Normalized TC
(Dwivedi et al., 2021)	1269	253.80	28.91
(Klerkx et al., 2019)	889	127.00	18.36
(Hwang & Chien, 2022)	515	128.75	30.48
(Forcael et al., 2020)	247	41.17	10.67
(Sung et al., 2021)	177	35.40	4.03
(Demestichas & Daskalakis, 2020)	148	24.67	6.40
(Chiarini, 2021)	145	29.00	3.30
(Shirowzhan et al., 2020)	135	22.50	5.83
(Jagtap et al., 2020)	131	26.20	2.98
(Gul & Bano, 2019)	131	18.71	2.71

As suggested in Table 3, Dwivedi et al. (2021) have the greatest number of citations, which emphasizes the significance of the article in the development of the research domain of digital technology adoption. Similarly, highly cited studies such as Klerkx et al. (2019) and Hwang (2022) make a significant contribution to the field's intellectual structure.

Therefore, these influential studies are cited within the context of the present review to identify the emerging themes and highlight the foundational studies that are informing the current body of knowledge in the domain of AR–AI–STEAM studies. Moreover, apart from the citation metrics presented in Table 3, Figure 7 illustrates the citation performance of the most globally cited studies.

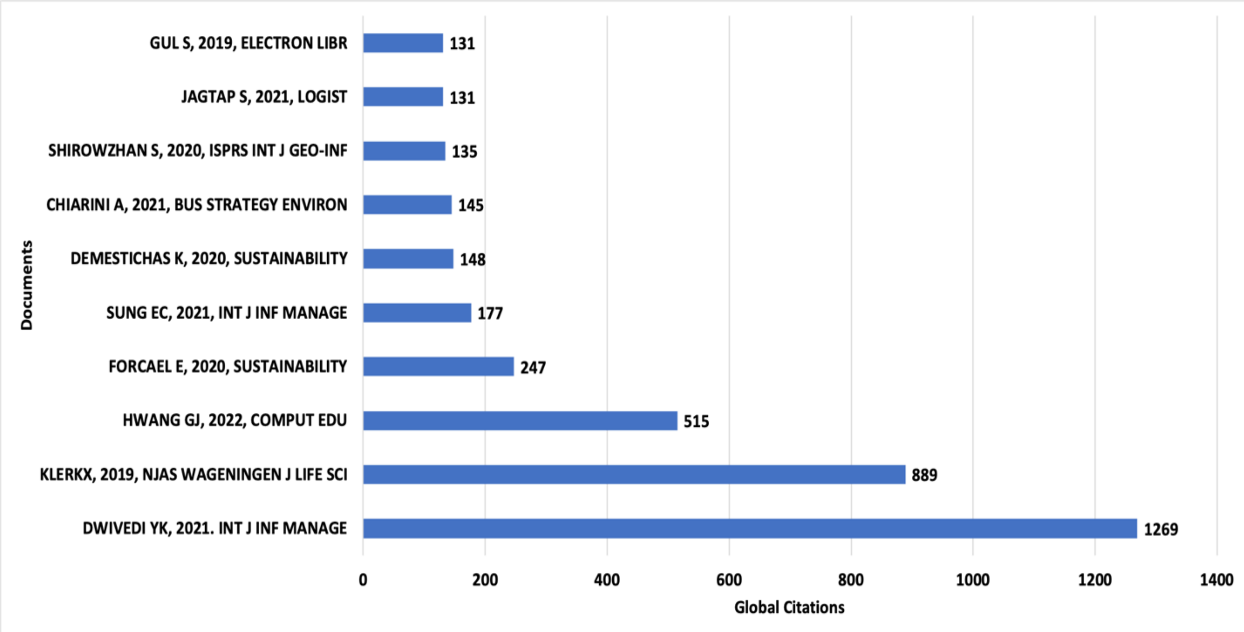

Figure 7. Most Globally Cited Documents

The table showing the most-cited documents worldwide reveals that the study by Dwivedi et al. (2019) is the most cited, with a total of 1,269 citations and a notably high rate of annual citations, which is 253.80. This is a clear indication that the study is significantly influential in the AR-AI-STEAM research domain. The unusually high normalized citation rate of 28.91 for the study also supports the argument that the study is significantly influential in comparison to the average rates observed in similar studies. The influence of the study by Hwang et al. (2022), is also significant, as the study is cited more than 500 times. However, the rate of annual citations is lower than that observed in the study by Dwivedi et al. The trend observed in the study by Hwang et al. is similar to the trend observed in similar studies in the broader research area. In the last few years, studies focusing on sustainability and educational technology have been at the center of the research area.

The notable citation rate observed in the study by Dwivedi et al. also reveals that the citation rate is significantly influenced by the influence of interdisciplinary studies, including the studies in the Sustainability and Business Strategy and Environment sections. The notable citation rate observed in the studies focusing on sustainability is a clear indication that the influence of interdisciplinary studies is significant. The notable citation rate observed in the studies focusing on sustainability is a clear indication that the influence of interdisciplinary studies is significant. The notable variation in the normalized citation rate, which ranges from a maximum of 30.48 to a minimum of 2.71, is a clear indication that the influence of the studies is not the same. The notable influence observed in the studies is a clear indication that the influence of interdisciplinary studies is significant. The notable variation in the normalized citation rate, which ranges from a maximum of 30.48 to a minimum of 2.71, is a clear indication that the influence of the studies is not the same. The notable influence observed in the studies is a clear indication.

Conceptual Structure and Thematic Evolution

The keyword co-occurrence map, as depicted in Figure 8, offers an overview of the conceptual landscape of AR, AI, and STEAM. At its center, we can see that artificial intelligence emerges as a significant hub that brings together different facets of edtech, such as personalized learning, student motivation, and immersion. However, wetland-related keywords (e.g., wetland, ecosystem conservation, and environmental education terms that explicitly indicate wetland contexts) appear peripheral and weakly connected to the central AI-oriented cluster. This pattern suggests a thematic disconnect between rapidly expanding AI-driven education discourse and ecologically grounded wetland learning contexts.

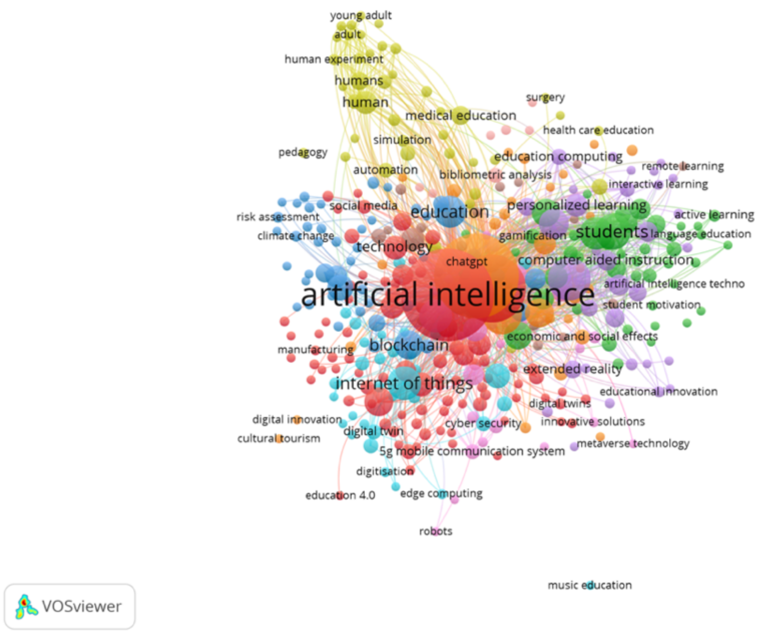

Figure 8. Keyword Occurrence

The conceptual structure of the keyword co-occurrence map visualized using VOSviewer shows that "artificial intelligence" is the main center of conceptual networks in the field of research analyzed. This node has the largest size, indicating a high frequency of occurrences, and is the main link between other themes such as education, Internet of Things, blockchain, personalized learning, and student motivation. This mapping indicates that artificial intelligence is not only the dominant topic but also a binding theme across domains, including digital technology, pedagogy, and technology-based learning systems.

Overlay visualization (Figure 9) further indicates temporal shifts in dominant themes. Recent growth is associated with terms such as personalized learning, extended reality, metaverse-related discourse, and generative AI-related keywords. Earlier themes (e.g., foundational education technology topics) remain present but appear less central in the most recent period. Importantly, the emergence of new technology terms does not necessarily imply maturation of wetland-specific applications; instead, the maps suggest that wetland learning remains under-integrated within the mainstream AR/AI discourse.

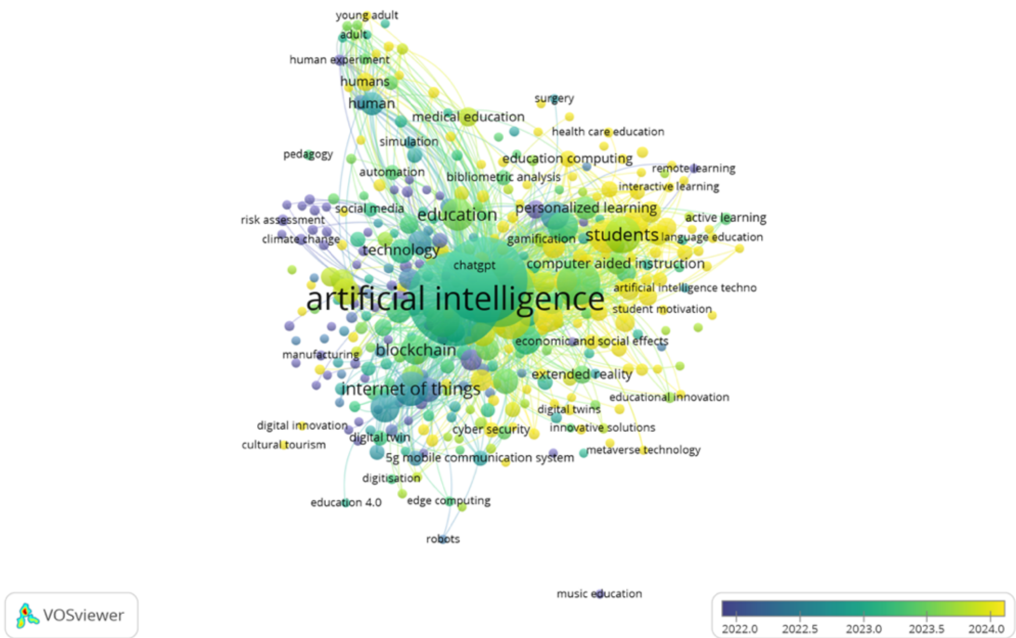

Figure 9. Thematic Evolution using VOS Viewer

Thematic evolution analysis based on overlay visualization in VOSviewer is used to map the shift in research focus over time, especially in the context of technology integration such as artificial intelligence (AI), internet of things (IoT), and learning approaches in the realms of education, technology, and health. This visualization shows theme changes based on the average year of publication, with a color scheme that shows the chronology of keyword occurrence: dark blue marks dominant old topics before 2022, green indicates a transition around 2022–2023, and bright yellow represents new topics that are growing rapidly in 2023 to 2024. The timescale is clearly displayed in the bottom right of the visualization to help with systematic temporal reading.

To align conceptual mapping with the 6C framework, Table 4 provides a thematic interpretation of clusters as “6C-related discourse alignment.” This table is intended to strengthen theoretical alignment, not to claim empirically measured 6C outcomes.

Table 4. Cluster Interpretation and Alignment with 6C-related Competencies (Interpretive Mapping)

Cluster (VOSviewer color)	Dominant keywords (representative)	Thematic focus (interpretation)	6C alignment (Primary → Secondary)	Rationale (why this cluster aligns with 6C)
Cluster 1 – AI-centered learning & analytics (node dominate: “artificial intelligence”)	artificial intelligence, education, personalized learning, student motivation (also connected to IoT, blockchain)	AI as a "hub" that binds the theme of pedagogy and data-based learning systems (adaptive/personalized).	Critical thinking → Communication, Character	CT: AI discourse is strong on data-driven decision-making, problem solving, and reasoning in adaptive learning. Com: AI is often present as a feedback/interaction system (chatbots, tutoring systems). Char: covers AI ethics/accountability issues (though not always explicit), related to integrity and responsibility.
Cluster 2 – Core digital infrastructure & security (red)	blockchain, cybersecurity, edge computing	Infrastructure and technology security as the foundation of the digital learning ecosystem (trust, privacy, governance).	Citizenship → Character, Critical thinking, Communication	Cit: Digital citizenship literacy (rights, privacy, data security) is closely related to cybersecurity/governance. Char: ethics of technology use, responsibility, security discipline. CT: risk analysis & system reliability evaluation. Com: the ability to convey/interpret risk information and security policies.
Cluster 3 – Health/medical education & simulation (Yellow)	human experimentation, medical education, simulation	Utilization of AR/AI for simulation and experiment-based training (especially health/medical education).	Collaboration → Communication, Critical thinking, Character	Col: medical simulations tend to be team-based (role coordination). Com: procedural communication and clinical/scenario

Cluster (VOSviewer color)	Dominant keywords (representative)	Thematic focus (interpretation)	6C alignment (Primary → Secondary)	Rationale (why this cluster aligns with 6C)
				communication. CT: clinical reasoning, diagnosis/decision-making. Char: professionalism, safety, ethics (human experimentation).
Cluster 4 – Gamification & active learning (Green)	gamification, active learning, education computing	Learning innovations that emphasize engagement, activities, and learning experience design strategies.	Creativity → Collaboration, Communication, Critical thinking	Cr: game design, creative activities, and learning experience engineering. Col: a lot of teamwork/competition-based gamification. Com: activity-based interaction and reflection. CT: decision-making in game-based problem contexts.
Cluster 5 – XR/metaverse & immersive learning ecosystem (purple)	metaverse technology, extended reality, digital twins	An immersive learning ecosystem (XR/metaverse/digital twins) that enables the representation and exploration of virtual environments.	Communication → Creativity, Collaboration, Critical thinking	Com: multimodal communication & typical XR (visual-spatial/simulative) representations of information. Cr: creation/design of immersive artifacts. Col: shared virtual spaces dan co-presence. CT: spatial reasoning, inquiry, hypothesis testing in simulation.
Cluster 6 – Sustainability & environmental discourse (appearing strongly on the old/grounded theme; "climate change" etc.)	climate change, pedagogy (and related environmental themes)	Environmental themes as a conceptual foundation; become the basis for ecological contexts, including opportunities to strengthen wetland contexts (although they are still weak in connection with AI hubs).	Citizenship → Character, Critical thinking, Communication	Cit: SDGs orientation, ecological responsibility, environmental literacy. Char: sustainability values/ethics. CT: systems thinking & ecological reasoning. Com: science communication (environmental data-based argumentation).
Cluster 7 – Online/remote learning & socio-	remote learning, economic and	Distance learning transition and socio-economic impact; generative AI	Communication → Critical thinking,	Com: digital communication literacy, online interaction, and the use

Cluster (VOSviewer color)	Dominant keywords (representative)	Thematic focus (interpretation)	6C alignment (Primary → Secondary)	Rationale (why this cluster aligns with 6C)
economic effects (New themes on Overlay 2023–2024)	social effects, ChatGPT	integration (ChatGPT) as a new phenomenon.	Character, Collaboration	of AI for academic communication. CT: evaluation of information and quality of AI output. Char: academic integrity, ethics of using AI. Col: coordination of distance learning and online collaborative work.

Notes: CT = Critical Thinking; Com = Communication; Col = Collaboration; Cr = Creativity; Char = Character; Cit = Citizenship.

Identifying Research Gaps

To identify research gaps in the current literature landscape, a time-based thematic analysis was conducted using the overlay visualization feature in VOSviewer. Figure 9 presents the results of thematic evolution that illustrate the dynamics of the emergence and development of keywords from year to year. Through this map, it is possible to recognize the topics that dominated in the previous period, themes that are currently undergoing transitions, and new themes that are on the rise. In addition, this visualization allows the search for empty areas among different clusters, representing potential thematic disconnections or a lack of cross-topic exploration. Thus, this analysis becomes an important basis for highlighting untapped research spaces and offering opportunities for future scientific contributions.

The results of the overlay visualization analysis using VOSviewer allow for a sharper identification of research gaps in the thematic map of the literature. One of the main indicators that reflects the existence of gaps is the existence of white spaces between several keyword clusters. For example, in the visualization analyzed, no connection was found between the topic of artificial intelligence, which is very dominant, and concepts from environmental contexts such as wetland, ecosystem, environmental education, or climate-resilient learning. The reality is that topics like education and personal learning continue to appear quite frequently. The gap indicates that advancing technology, especially in relation to artificial intelligence, in the local ecological setting, especially in relation to wetland education, is quite large.

In addition, color analysis on keyword nodes also provides important insights related to thematic evolution. The bright yellow color represents new themes that are emerging and growing rapidly in 2023–2024, such as ChatGPT, personalized learning, extended reality, student motivation, and remote learning. These topics are very promising to be the focus of further research, including in terms of effectiveness, ethics, and cross-field integration. In contrast, dark blue nodes such as education 4.0, social media, blockchain, and climate change represent themes that are starting to lose their study intensity, but remain relevant to be reviewed in the context of recent trends. Furthermore, several theme pairs were found that were not connected, such as artificial intelligence with wetlands or ESD, gamification with biodiversity, and metaverse with place-based education. This disconnection indicates the potential for integrative gaps that can be filled by interdisciplinary research. Therefore, future research is suggested to explore the integration of AI with wetland education, the convergence of STEAM–ESD–AI, as well as the application of metaverse technology in the context of environmental conservation and locally-based learning. These results appear to support the notion that despite the advanced status of high-tech topics, their association with sustainability, as well as the context-aware educational concept, is limited, thus providing prospects for more informed scientific contributions.

Discussion

Looking at the trend, it can be observed from the bibliometric data that after 2022, there was a rapid increase in activities and research involving AR, AI, and STEAM in education, emphasizing a rising interest in AI-related education technology all over the globe. On another level, when looking at terms, there is an overwhelming presence of AI-related terms, which signifies that while AI-related systems have become an essential element when discussing education technology, terms related to wetlands are relegated to the fringes, while environmental-related ideas are integrated into concepts involving climate change.

This suggests that research is now driven by evidence. Rather than churning out more tech-oriented research studies, scholars should concentrate on bridging research that makes AI and immersive techniques palpable in wetland learning. This entails context-sensitive pedagogy, geography-oriented environmental literacy, and ethics-oriented sustainability education. Of immediate interest is that in order to achieve these perspectives, one needs research methods that transcend bibliometric research to include intervention study, design research, and evaluation research.

The rise in published works addressing the intersection of Augmented Reality (AR), Artificial Intelligence (AI), and STEAM signifies a change in the scope of published content towards digital-age constructs, such as the concept of the 6C framework and how it could be integrated into ideas such as environmental education in relation to a topic such as the ecosystem of the wetland environment. As can be seen in the data, there was a significant increase in published works in the year 2025 (approximately 249 records), though care must be taken with such results, particularly because the end cut-off for our search was February 12, 2025, and the indexers may not have had enough time to populate that information yet. The results in later years do reflect the push towards active learning methods that are further supported with richer learning resources (E. Cho et al., 2023; Kabathova & Drlik, 2021; Kim et al., 2023).

Despite this, as one peruses the keywords represented in the conceptual map of the body of work, though "artificial intelligence" appears as the dominant term across all the literature, the degree to which it is related to other terms like "wetland education" or "ecosystem conservation" remains vague. This further suggests a thematic fragmentation with regard to the discourse on the integration of technology, wherein the pace appears to be too quick for the more specific grounding in ecological or geographical terms with regard to the tech-oriented literature.

The findings make sense in relation to existing research that argues that our experience with COVID-19 has accelerated how technology is realized in education globally, in addition to exposing relationships to the ability to access technology and how relevant it is in different venues (Zawacki-Richter et al., 2019). In that sense, our investigation suggests that learning spaces that recognize sustainability and focus on wetlands are relatively disconnected from the dominant scholarly conversation on AI in relation to sustainability education. The disconnection can be seen in relation to how increased engagement with technology has yet to produce an established line of research that explicitly develops the connection to sustainability education through AI. Moreover, no direct conceptual connection between terms related to a concept of metaverse and a field of wetland ecosystems was detected by the co-occurrence analysis, while there are hints of a gradually developing interest regarding mixed reality in terms of environmental learning (Ivanova et al., 2024; Prahani et al., 2022; Qin & Zhang, 2025). The absence of the above connections, however, should not be seen in terms of a lack of prospects but rather in terms of an opportunity, in which local biodiversity and learning in terms of wetland ecosystems might fuel a blend of STEAM and mixed reality approaches.

From a theoretical standpoint, findings push us to consider weaving ecological context more explicitly into technology-pedagogy work within digital learning. In other words, they support the ecotechnological approach to teaching, one which ties digital competence talk with sustainability values and ethics (Beetham & Sharpe, 2019; Cowling et al., 2022; Fischer et al., 2020). Put this way, AR-AI-driven wetland learning isn't just a gleaming new tool but can become a conduit for ecosocial awareness, provided learning designs clearly make connections between what technology can do and place-based sense-making and sustainability ethics. In practice, these identified gaps and disjunctures in themes could be useful in continuing the development and assessment of the ARAiLand module as a contextualized and holistic prototype for technology-based education in wetlands. In the classroom, these themes could be used to facilitate contextualized scientific inquiry in education; in policy circles, these could be used to consider the integration of augmented reality and artificial intelligence in environmental education as a promising approach to advancing education for sustainable development, with particular pertinence to SDG 4 and SDG 15 (Blom & Karrow, 2024; Colás-Bravo et al., 2021; García-Hernández et al., 2022). This pertinence assumes particular significance in regions that are home to critical ecosystems like swamps or peatlands, especially in the face of rising climate-related risks.

Although the utility of bibliometric mapping in characterizing the global research landscape is significant, there are still limitations to be considered. First, the limitation of the dataset to English-language publications included in the Scopus database may not represent the research literature, particularly those from the Global South that are often published in local languages or not included in the database (Karabay & Durrani, 2024; Wu & Tsai, 2024). Second, although ResearchRabbit provides an AI-assisted mechanism for expanding citation trails, it may introduce semantic or network-driven bias because recommendations are shaped by linkage patterns rather than empirical validation (Alazemi, 2024; Giarimpampa et al., 2025; Naqvi et al., 2024). Third, the study does not include empirical implementation or trials of the ARAiLand module; therefore, any practical implications should be treated as prospective rather than evidential.

These limitations are consistent with the exploratory purpose of bibliometric studies, which aim to map research landscapes and identify gaps rather than test causal hypotheses or intervention effectiveness. At the same time, they point directly to the next research steps. First, field-based empirical research is needed to examine the effectiveness of the ARAiLand module in fostering students' 6C-related competencies in wetland contexts, for example, using quasi-experimental and mixed-method designs that integrate quantitative and qualitative evidence (DeCuir-Gunby et al., 2024; DeCuir-Gunby & Johnson, 2025a, 2025b). Second, longitudinal studies would be valuable for assessing the sustained impacts of immersive learning on sustainability literacy and environmental ethics over time. Third, expanding outcome lenses to more explicitly include citizenship and character in local ecological contexts may strengthen the humanistic and ethical dimensions of technology-based environmental education. Fourth, interdisciplinary exploration that integrates metaverse-related learning, gamification, and place-based education offers promising pathways for designing ecologically relevant STEAM learning experiences (Lin & Chen, 2023; Wagner & Liu, 2021; Wu et al., 2021). The enhancement of collaboration both within and across borders and institutions, particularly for the interconnection of the developing context with the established educational technology centers, is still significant in the attempt to forge a knowledge ecosystem that is more inclusive, taking into account the complexities and challenges of global sustainability issues.

LIMITATIONS

It must be mentioned that there are a few limitations of this research that need to be considered while interpreting the results. The research was based on Scopus results, which are based on English literature. However, other research could also be conducted in different global regions that were not considered in this research. Second, the retrieval date (12 February 2025) means that records labeled as 2025 reflect an early-year snapshot; therefore, comparisons involving 2025 should be treated as provisional and may be influenced by indexing dynamics rather than complete annual output. Third, bibliometric analyses depend on the quality and consistency of bibliographic metadata; despite applying deduplication, author–affiliation disambiguation, and keyword normalization, residual inconsistencies may still affect collaboration and co-occurrence maps. Fourth, ResearchRabbit was used as a complementary AI-assisted exploration tool to extend citation trails and identify semantically proximate literature candidates; however, its recommendation mechanism is network- and similarity-driven, which may introduce semantic bias and should not be interpreted as exhaustive coverage. Finally, because this research is bibliometric in nature, it maps publication patterns and conceptual linkages but does not provide empirical evidence of instructional effectiveness or measured gains in 6C-related competencies; such claims require intervention-based and mixed-method studies in authentic wetland learning contexts.

CONCLUSION

This bibliometric mapping (2019–2025; retrieved from Scopus on 12 February 2025) shows a marked growth of AR–AI–STEAM publications after 2022, with China, India, and the United States among the most productive contributors. Conceptual mapping identifies "artificial intelligence" as a dominant hub that connects multiple educational technology themes, while wetland-related terms remain peripheral and weakly connected, indicating a thematic gap between rapidly expanding AI-driven discourse and ecologically grounded wetland learning contexts. The patterns of collaboration indicate that the majority of the productivity is accounted for by a few key hubs, and the international regional connectedness varies significantly. Consequently, a clear picture emerges of the research field, where gaps in the links are pointed out for future studies and design for wetland education. Since the 2025 data is collected early in the year for the year 2025, any trends must be viewed provisionally.

AUTHOR CONTRIBUTIONS

All the authors were actively involved throughout the research and the manuscript. RR was responsible for the conceptualization of the research, outlining the methodology, conducting the main research analysis, supervising the research, and creating the initial draft of the manuscript. On the other hand, SS was responsible for the research investigations, validation of the findings, developing a visualization of the results through various tools such as Bibliometrix and VOSviewer, as well as reviewing the manuscript with edits. FE was responsible for carrying out the literature searches, validating the research findings, developing bibliometric search queries, and managing the references used in the manuscript. AEK was responsible for additional research findings, creating a visualization of the results, as well as making critical contributions to the manuscript. Finally, LTT was responsible for methodology guidance, making the manuscript more global, as well as carrying out the final manuscript proofreading.

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