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Mapping augmented reality and inquiry learning for critical thinking and instructional materials development: a bibliometric analysis based on dimensions data

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ABSTRACT

This bibliometric study investigates the global research landscape of augmented reality (AR) and inquiry-based learning (IBL) as integrated instructional approaches for promoting critical thinking skills and supporting instructional materials development. Using data retrieved from Dimensions, one of the world's largest scientific databases, this study analyzed 500 articles published between 2017 and 2026. Keyword co-occurrence, overlay visualization, and density mapping were conducted using VOSviewer. Results indicate a dramatic increase in publication volume, from 27 articles in 2017 to 631 in 2025, confirming growing global scholarly interest. Four dominant research clusters were identified: (1) technology integration and science education, (2) learning outcomes and inquiry-based models, (3) research instruments and quantitative methods, and (4) higher-order thinking skills. Overlay visualization confirmed that the most recent research trends center on e-modules, HOTS, creativity, and 21st-century skills, reflecting a pedagogical shift toward competency-based and student-centered learning. Density analysis revealed that "effect," "model," "technology," and "test" are the most intensively investigated topics. The findings imply that AR-supported inquiry learning has strong potential to guide the design of innovative instructional materials, particularly digital worksheets and e-modules, that promote critical thinking and higher-order learning. This study also provides practical insights for educators, curriculum developers, and researchers in identifying emerging themes, underexplored areas, and future directions for technology-enhanced inquiry-based instruction

1. Introduction

The rapid advancement of educational technology has fundamentally transformed instructional paradigms across global contexts. In the contemporary knowledge-based economy, quality education has emerged as a critical pillar of sustainable development, as reflected in the United Nations Sustainable Development Goal 4 (SDG 4)[1], which calls for inclusive and equitable quality education and lifelong learning opportunities for all [1]. Amid this transformation, the integration of immersive and interactive technologies particularly Augmented Reality (AR) has garnered substantial scholarly attention as a promising vehicle for enhancing learning outcomes, fostering student engagement, and developing higher-order thinking skills [2,3,4]. Concurrently, inquiry-based learning (IBL) has been widely endorsed as a pedagogical framework aligned with constructivist principles, enabling learners to construct knowledge through active exploration, questioning, and problem-solving [5]. The convergence of AR and IBL represents an innovative instructional paradigm with significant implications for critical thinking development and the design of contextually relevant instructional materials.

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A growing body of empirical research has documented the effectiveness of AR in various educational settings. Studies in science education, for instance, have demonstrated that AR-enhanced learning environments significantly improve conceptual understanding, spatial reasoning, and student smotivation [6,9]. In the context of inquiry-based learning, AR applications have been used to simulate laboratory experiments, visualize abstract phenomena, and scaffold complex investigations that would otherwise be inaccessible within conventional classroom settings[10,13]. These developments have been particularly notable in STEM disciplines, where the abstract nature of content frequently poses cognitive barriers for learners. Research conducted across Asia, Europe, and North America has consistently shown positive effects of AR-IBL integration on academic performance and critical thinking competencies [14, 15]. Nevertheless, despite these promising findings, the research landscape remains fragmented, with studies often limited to narrow disciplinary contexts or short intervention durations.

Despite the accumulating body of empirical research on AR and inquiry-based learning, a systematic and quantitative overview of the global research trajectory of this intersection remains notably absent. Existing reviews have largely employed narrative or systematic methodologies, which, while insightful, are susceptible to selection bias and do not provide a macroscopic view of the intellectual structure of the field [16]. Furthermore, no prior bibliometric analysis has comprehensively examined the co-occurrence patterns of keywords, the temporal evolution of research topics, and the density distribution of themes within the specific nexus of AR, inquiry-based learning, critical thinking, and instructional materials development. The Dimensions database, which indexes a broader scope of scholarly outputs compared to traditional databases, provides an unparalleled opportunity for such a comprehensive analysis [17]. This gap underscores the necessity for a rigorous bibliometric study that maps the global intellectual landscape of this research domain from 2017 to 2026.

The novelty of this study lies in its adoption of a multi-layered bibliometric approach to systematically map the intellectual structure of AR- and IBL related research with a specific focus on critical thinking and instructional materials development. Unlike previous reviews that rely on a single database or narrow keyword set, this study employs Dimensions a comprehensive multidisciplinary database combined with VOSviewer for advanced network visualization, enabling the identification of thematic clusters, emerging research fronts, and collaborative networks. [18, 19] The analytical scope encompasses keyword co-occurrence analysis, overlay visualization for temporal trend mapping, and density visualization for knowledge concentration assessment. This integrative approach provides an empirically grounded and methodologically robust foundation for understanding how the field has evolved and where it is heading.

This study addresses the following research questions: (1) What are the annual publication trends in research on AR and inquiry-based learning for critical thinking and instructional materials development from 2017 to 2026? (2) What thematic clusters emerge from keyword co-occurrence analysis in this research domain? (3) How have research topics temporally evolved according to overlay visualization? (4) What are the most densely investigated research themes based on density visualization? (5) Who are the most productive authors, and what are the most active journals in this research area?

The primary objective of this study is to provide a comprehensive bibliometric map of the global research on AR and IBL within the context of critical thinking and instructional materials development, drawing from data available in the Dimensions database. Specifically, this study aims to: (1) identify the annual publication growth patterns and key temporal milestones; (2) delineate the major thematic clusters and keyword networks in the field; (3) trace the temporal evolution of research topics; (4) determine the most densely researched areas; and (5) identify the most prolific authors and journals. These findings are intended to guide future research directions, inform pedagogical practice, and support evidence-based educational policy in the integration of AR and inquiry-based learning.

2. Method

This study employed a bibliometric analysis design, which is a quantitative approach to mapping the intellectual structure, thematic evolution, and collaborative networks within a body of scientific literature [16, 20, 21]. Bibliometric methods have been increasingly recognized as rigorous tools for conducting systematic literature reviews in education and technology research, offering the capacity to analyze large volumes of publications with precision and reproducibility [22, 23]. Data were retrieved from Dimensions (https://app.dimensions.ai), a comprehensive multidisciplinary academic database that indexes research outputs across all fields of knowledge and offers advanced export functionalities including RIS and CSV formats [17]. The search query was structured using Boolean operators combining the primary constructs of the study: ("augmented reality" OR "AR technology") AND ("inquiry learning" OR "inquiry-based learning") AND ("critical thinking" OR HOTS) AND (education). The search was restricted to peer-reviewed journal

articles published between 2017 and 2026, yielding an initial dataset of 500 records after applying field-of-research filters: Education (ANZSRC 39 Education, 3901 Curriculum and Pedagogy, 3902 Education Policy, Sociology and Philosophy, 3903 Education Systems, and 3904 Specialist Studies in Education). Document selection followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol [18, 21, 24] which involved four stages: identification of records, screening based on title and abstract relevance, eligibility assessment based on full-text availability and thematic alignment, and final inclusion. Records that did not address at least two of the three core constructs (AR, inquiry-based learning, and critical thinking/HOTS) were excluded from the analysis. Duplicates were removed using the deduplication feature within Dimensions before export.

The bibliometric analysis was conducted using VOSviewer (version 1.6.20), a widely validated software for bibliometric network visualization and analysis [20]. The steps of analysis Fig. 1 can be seen in below.

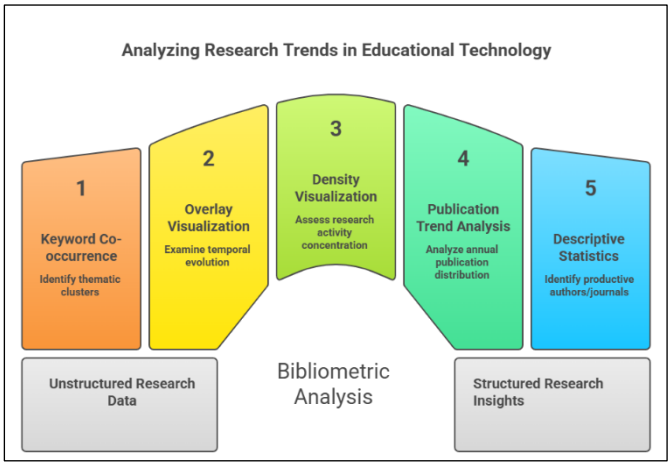


Fig. 1. Analysis research

Three types of analyses were performed. First, keyword co-occurrence analysis was conducted to identify the thematic clusters and conceptual associations within the dataset, with a minimum occurrence threshold of three per keyword. This analysis produced a network visualization in which nodes represent keywords, node size reflects occurrence frequency, and link thickness indicates co-occurrence strength. Second, overlay visualization was employed to examine the temporal evolution of research topics by color-coding each keyword node based on the average publication year of documents in which it appears, thereby revealing emerging and declining research themes. Third, density visualization was used to assess the concentration of research activity around specific thematic nodes, with warmer colors indicating higher keyword density and scholarly attention. Additionally, publication trend analysis was conducted on the annual distribution of publications, while descriptive statistics were computed to identify the most productive authors and journals. All data processing, including deduplication and network parameter setting, followed established protocols for bibliometric studies in educational technology research [25, 26]. Reference management and citation formatting were handled using Mendeley Desktop, and all references were verified against the Dimensions and Scopus databases to ensure accuracy.

3. Results and discussion

3.1. Results

Fig. 2 presents the annual distribution of publications on augmented reality and inquiry-based learning for critical thinking and instructional materials development from 2017 to 2026, based on data retrieved from the Dimensions database.

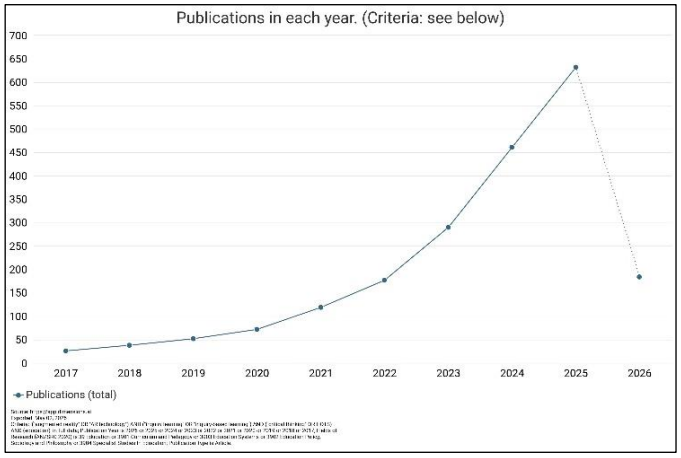


Fig. 2. Annual publication trends (2017–2026) on AR, inquiry-based learning, and critical thinking. Source: Dimensions (2026)

The data reveal a consistent and accelerating upward trajectory in global research output across the study period. As summarized in Table 1, the number of publications grew from 27 articles in 2017 to a peak of 631 in 2025, representing an increase of over $\mathbf{2,237}$% within a span of eight years. This exponential growth reflects the intensifying global scholarly interest in the convergence of augmented reality technology, inquiry-based pedagogy, and higher-order thinking skills development. The most pronounced growth phases occurred between 2020 and 2021 ($+\mathbf{71.4}$%) and between 2022 and 2023 ($+\mathbf{64.0}$%), coinciding with the global expansion of digital and remote education practices accelerated by the COVID-19 pandemic. These periods saw educational institutions worldwide adopting immersive technologies and active learning frameworks to sustain instructional quality in non-traditional learning environments [10, 27]. The 2026 figure of 185 publications represents only a partial year

(data exported on May 2, 2026) and is thus not indicative of declining output.

Table 1
Annual Publication Distribution (2017–2026)

Year	Number of Publications	Growth Rate (%)
2017	**27**	–
2018	**39**	**+44.4**
2019	**54**	**+38.5**
2020	**70**	**+29.6**
2021	**120**	**+71.4**
2022	**178**	**+48.3**
2023	**292**	**+64.0**
2024	**463**	**+58.6**
2025	**631**	**+36.3**
2026*	**185**	(partial)

*2026 data is partial (exported May 2, 2026)

These findings are consistent with broader bibliometric studies in AR-based education [15, 28] and inquiry-based science learning [5], which have similarly documented sustained growth in publication volume. The surge post-2021 may also be attributed to the increasing accessibility of AR development tools and the proliferation of low-cost mobile AR devices, which have lowered the barriers to AR-based instructional design research [2]. The trend strongly suggests that research in this domain will continue to expand, with growing focus on pedagogical effectiveness, design principles, and contextual adaptations across different educational systems and cultural settings.

3.2. Keyword Co-Occurrence Network Analysis

Fig. 3 presents the keyword co-occurrence network generated by VOSviewer from the 500 articles retrieved from Dimensions. The network visualization reveals the relational structure of research topics and thematic clusters within the domain of augmented reality, inquiry-based learning, critical thinking, and instructional materials development.

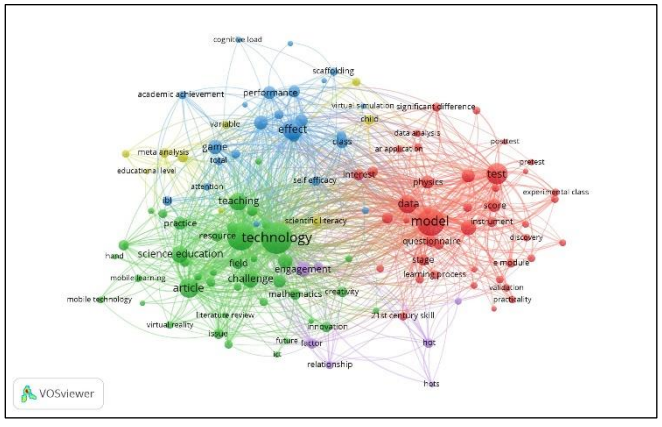


Fig. 3. Keyword co-occurrence network visualization.

The network analysis identified four distinct thematic clusters, each represented by a unique color in the visualization. The first cluster (green) is the largest and encompasses terms such as "technology," "science education," "article," "teaching," "engagement," "challenge," and "resource." This cluster represents studies focused on the integration of digital technology particularly AR within science education contexts, emphasizing pedagogical challenges, student engagement strategies, and resource mobilization. The dominance of this cluster confirms that science education remains the primary disciplinary home for AR and inquiry-based learning research [29, 30]. The second cluster (blue) groups terms including "effect," "performance," "game," "class," "scaffolding," and "cognitive load," reflecting a strong emphasis on measuring the learning effects of technology-enhanced inquiry instruction, including gamification elements and cognitive scaffolding. This cluster highlights the prominent role of experimental and quasi-experimental research designs in assessing instructional interventions [31, 33]

The third cluster (red) contains "model," "test," "data," "questionnaire," "score," "instrument," "physics," "e-module," "validation," and "practicality" terms closely associated with the development and psychometric validation of instructional materials in physics education, particularly in Indonesian educational contexts. The prevalence of "e-module," "validation," and "practicality" is indicative of a substantial body of Indonesian scholarship on developing and testing AR-integrated digital modules within national curriculum frameworks [34, 35]. The fourth cluster (purple) groups "HOTS," "hot," "21st century skill," and "relationship," representing an emerging research focus on the connections between AR-IBL instruction and higher-order thinking skills (HOTS) aligned with 21st-century competency frameworks. This cluster, while smaller, reflects a growing policy-driven research agenda that aligns with global education reform movements [33, 36, 37]. The interconnections across clusters reveal that the field is not siloed; rather, researchers increasingly draw on cross-cluster concepts, suggesting a maturing and integrative intellectual community.

Table 2 presents the most productive authors contributing to this research domain. Kuswanto (Universitas Negeri Yogyakarta, Indonesia) leads with four publications, followed by Zheng, Wen, Lin, Li, Fadillah, Cai, and Wiyanto, each with three publications. The geographical distribution of top authors reveals a concentration in Indonesia, China, Singapore, and Taiwan, underscoring the centrality of the Asia-Pacific region in AR and IBL research. This finding aligns with prior bibliometric studies identifying Southeast and East Asian institutions as prominent hubs for educational technology innovation [38].

Table 2
Most Productive Authors (2017–2026)

No.	Author	Institution	Publications
1	Kuswanto, H.	Universitas Negeri Yogyakarta, Indonesia	4
2	Zheng, L.	Beijing Normal University, China	3
3	Wen, Y.	Nanyang Technological University, Singapore	3
4	Lin, X.-F.	South China Normal University, China	3
5	Li, P.-H.	National Taiwan University, Taiwan	3
6	Fadillah, M.A.	Universitas Negeri Surabaya, Indonesia	3
7	Cai, S.	Beijing Normal University, China	3
8	Wiyanto, W.	Universitas Negeri Semarang, Indonesia	3

Source: Dimensions database analysis (2026)

Table 3
Most Active Journals (2017–2026)

No.	Journal Name	Publisher	Articles
1	Jurnal Penelitian Pendidikan IPA	Indonesia	27
2	Education and Information Technologies	Springer	21
3	Interactive Learning Environments	Taylor & Francis	15
4	Journal of Science Education and Technology	Springer	14
5	International Journal of Information and Education Technology	IACSIT	14
6	Journal of Computer Assisted Learning	Wiley	12
7	Heliyon	Elsevier	11
8	Computers & Education	Elsevier	8

Source: Dimensions database analysis (2026)

Table 3 lists the journals with the highest publication counts. Education and Information Technologies (Springer) leads international journals with 21 publications, followed by Interactive Learning Environments (15) and the Journal of Science Education and Technology (14). Notably, Jurnal Penelitian Pendidikan IPA ranks first overall with 27 publications, indicating the particularly robust contribution of Indonesian science education researchers. The prominence of Elsevier's Computers & Education and the Journal of Computer Assisted Learning further affirms the centrality of educational technology journals in disseminating this research [16].

3.3. *Overlay Visualization: Temporal Research Evolution*

Fig. 4 presents the overlay visualization of the keyword co-occurrence network, in which node color represents the average publication year of documents containing each keyword, ranging from dark blue.

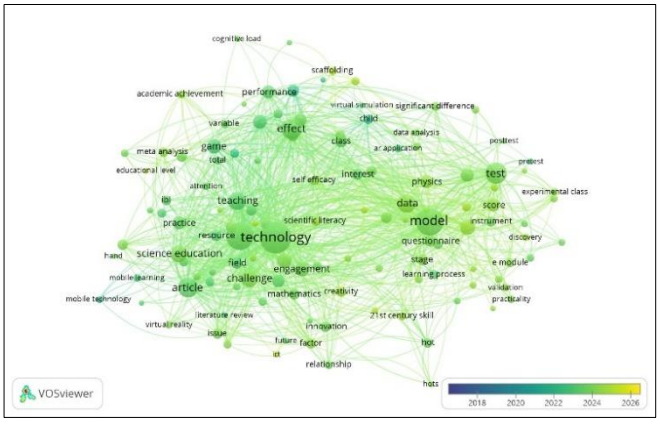


Fig. 4. Overlay visualization

The overlay visualization reveals a clear temporal stratification of research themes. Earlier research (approximately 2018–2020) was predominantly concentrated around foundational constructs such as "game," "variable," "meta analysis," "cognitive load," and "academic achievement," suggesting that initial scholarly efforts were directed toward establishing the theoretical and empirical foundations of AR and IBL-related interventions. These older themes, represented in darker tones (blue to teal), correspond to the first wave of AR research in education, which focused primarily on establishing proof-of-concept and effect-size documentation through meta-analyses and controlled experiments [7, 28]. In contrast, the most recently active themes (2023–2026), represented in bright yellow-green tones, include "e module," "HOTS," "creativity," "21st century skill," "innovation," "ict," and "discovery." The emergence of these keywords in the most recent cohort of publications reflects a paradigmatic shift in the field from proving that AR and IBL "work" to investigating how they can be purposefully designed to cultivate advanced cognitive competencies and align with national and international curriculum reform agendas [29, 39]. The appearance of "discovery" and "innovation" as recent keywords is particularly notable, as it points toward a growing research interest in discovery-based and project-based learning models enhanced by AR technology. This temporal map provides a strategic research roadmap: scholars entering this field would benefit from focusing on the intersection of AR, HOTS development, e-module design, and 21st-century skill cultivation within contemporary curriculum frameworks [4, 40, 41].

3.4. Density Visualization: Research Concentration

Fig. 5 presents the density visualization of the keyword network, in which the color gradient from dark blue (low density) to bright yellow (high density) indicates the relative concentration of scholarly attention around each keyword node.

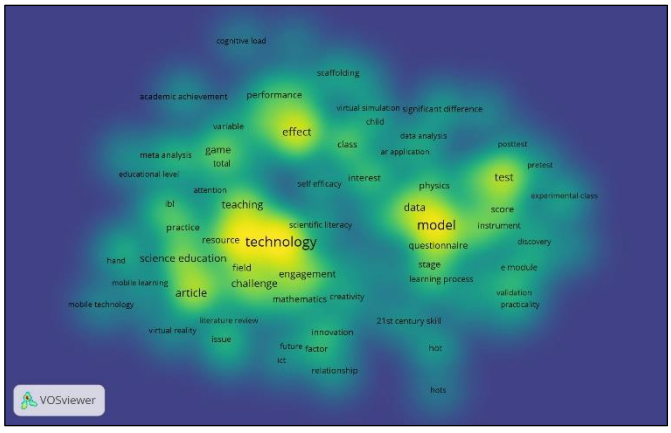


Fig. 5. Density visualization

The density map identifies four primary hotspots of research concentration: (1) "effect" located in the upper-central region of the network with the highest density, reflecting the field's preoccupation with measuring intervention effectiveness; (2) "model" and "data" centrally positioned and densely interconnected, indicating high scholarly activity around instructional model design and data-driven evaluation; (3) "test" and "score" positioned in the right region with high density, confirming the dominance of pre-test/post-test quasi-experimental methodologies in assessing learning outcomes; and (4) "technology" and "teaching" positioned in the central-left region, indicating sustained and broad scholarly engagement with technology integration in teaching practice [42 - 47].

The density map also reveals areas of relatively low scholarly concentration (dark blue), including "mobile technology," "virtual reality," "literature review," "issue," and "relationship." While these topics appear in the network, their lower density suggests they represent niche or emerging areas that have yet to attract concentrated research effort [48 – 50]. The relatively low density of "virtual reality" compared to "AR" may reflect the higher cost and accessibility barriers associated with VR technology in educational settings, particularly in developing countries that constitute a substantial portion of the publication base [2, 3]. The dominance of "effect," "model," and "test" as the densest nodes reflects a research culture that is heavily oriented toward quasi-experimental outcome measurement a finding that may signal the need for more diverse methodological approaches, including design-based research, longitudinal studies, and qualitative investigations of the learning process [51 – 64].

4. Conclusion

This bibliometric study comprehensively mapped the global research landscape of augmented reality and inquiry-based learning as applied to critical thinking and instructional materials development, drawing from 500 articles published between 2017 and 2026 in the Dimensions database. The findings provide answers to the research questions formulated in this study. First, the annual publication trend demonstrates substantial growth, increasing from 27 articles in 2017 to 631 in 2025, confirming that this research domain has gained increasing scholarly attention and continues to expand rapidly. Second, keyword co-occurrence analysis identified four coherent thematic clusters: technology-integrated science education, learning effects and experimental research, instructional materials development and validation, and higher-order thinking skills. Third, overlay visualization revealed that the field has evolved from foundational effectiveness studies toward more recent research agendas centered on HOTS, e-module design, creativity, and 21st-century skill cultivation. Fourth, density visualization confirmed that “effect,” “model,” “test,” and “technology” represent the most intensively investigated constructs, reflecting the dominance of intervention-based and quasi-experimental research in this field.

The theoretical contributions of this study are threefold. First, it provides a comprehensive bibliometric map of the intersection of AR, IBL, critical thinking, and instructional materials development, offering an intellectual overview of the field. Second, it identifies four major research clusters and their temporal evolution, which may serve as a conceptual reference for future literature reviews and research design. Third, the density analysis highlights areas of knowledge concentration and underexplored themes, providing a data-driven basis for identifying potential research gaps. Practically, the findings offer useful guidance for curriculum designers, AR developers, teachers, and educational policymakers in designing AR-enhanced inquiry-based learning experiences that are aligned with critical thinking development and 21st-century competencies.

Despite these contributions, this study has several limitations. The analysis was limited to journal articles indexed in the Dimensions database, which may exclude relevant studies from other databases such as Scopus, Web of Science, ERIC, or Google Scholar. The search strategy was based on selected keywords related to augmented reality, inquiry-based learning, critical thinking, and education; therefore, relevant studies using alternative terms such as immersive learning, discovery learning, problem-based inquiry, digital worksheets, or higher-order cognition may not have been fully captured. In addition, the 2026 data should be interpreted cautiously because it represents partial-year publication records and may not reflect the complete annual trend.

Future research should expand the data sources by integrating Scopus, Web of Science, ERIC, and Google Scholar to produce a more comprehensive bibliometric

map. Further studies are also recommended to conduct co-authorship, citation, bibliographic coupling, and co-citation analyses to reveal collaboration networks, influential authors, leading institutions, and intellectual foundations of the field. In addition, systematic literature reviews or meta-analyses should be conducted on specific sub-themes identified in this study, particularly AR-supported inquiry learning, AR-based e-modules, digital worksheets, HOTS, and critical thinking development. Empirical studies are also needed to examine the actual pedagogical impact of AR-IBL interventions across different educational levels, subject areas, and cultural contexts. Such future investigations would strengthen the evidence base and support the translation of bibliometric findings into practical instructional innovations.

CRediT authorship contribution statement

Edy Kurniawan: Conceptualization, Methodology, Data curation, Formal analysis, Writing original draft, Visualization, Project administration. Sudarman: Methodology, Validation, Supervision, Writing review & editing. Rahmad Bustanul Anwar: Validation, Formal analysis, Writing review & editing. Dwi Rahmawati: Data curation, Investigation, Visualization, Writing review & editing.

Declaration of Competing Interest

The authors declare that this study did not involve any conflicts of interest that could potentially influence the research process, data analysis, presentation of results, or preparation of the article.

Data availability

The data supporting the findings of this study were obtained from 500 articles published between 2017 and 2026.

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