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From 4C Skills to a Digital Competency Ecosystem: A Bibliometric Review of Essential Competencies in Contemporary Education

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Abstract

The rapid digitalization of education has expanded the competency agenda beyond the traditional 4C framework of critical thinking, creativity, communication, and collaboration. This study maps the development, structure, and thematic evolution of research on essential competencies in contemporary education, with particular attention to the relationship between the 4Cs and digital literacy, digital competence, computational thinking, information literacy, and related emerging competencies. A bibliometric review was conducted using 2,070 English-language Scopus-indexed documents published between 2015 and 2025. The analysis combined performance indicators with science-mapping techniques, including keyword co-occurrence, overlay and density visualization, country co-authorship analysis, bibliographic-link indicators, and thematic-evolution mapping. The corpus comprised 965 sources and 5,714 authors, with an annual publication growth rate of 19.72% and an average of 14.17 citations per document. Indonesia recorded the highest publication output, whereas the United States showed stronger citation impact and international collaboration among leading countries. The conceptual structure revealed a dense network linking 21st-century skills, creativity, collaboration, critical thinking, digital literacy, computational thinking, information literacy, and technology-supported learning. Temporal analysis showed increasing differentiation from early themes of digital literacies and programming toward digital skills, information and data literacy, digital competence, digital transformation, robotics, and AI-related learning. The findings indicate that digital literacy has not replaced the 4Cs. Instead, contemporary competency research is evolving toward an interconnected ecosystem in which the 4Cs remain foundational while increasingly integrating digital, computational, informational, pedagogical, assessment, and employability-oriented competencies. This synthesis clarifies the field's conceptual convergence and provides a basis for curriculum, assessment, and competency-development research worldwide.

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INTRODUCTION

Contemporary education is increasingly expected to prepare learners for environments characterized by rapid technological change, information abundance, interdisciplinary problem solving, and shifting professional demands. Educational success therefore cannot be

defined solely by the acquisition of disciplinary knowledge. Learners are also expected to evaluate information critically, generate and refine ideas, communicate effectively, collaborate with others, and respond adaptively to unfamiliar problems. Within this broader agenda, critical thinking, creativity, communication, and collaboration, commonly referred to as the 4Cs, have become enduring components of 21st-century competency frameworks. These competencies continue to influence curriculum design, teacher preparation, assessment, professional education, and employability because they represent capabilities required for meaningful participation in academic, social, and workplace contexts (Rios et al., 2020; Thornhill-Miller et al., 2023). Recent studies likewise continue to position the 4Cs as important educational outcomes across different disciplinary and institutional settings (Ha, 2025; Schmitz et al., 2024; Wardani et al., 2025).

The continuing relevance of the 4Cs, however, does not mean that the competency landscape has remained static. The increasing integration of digital technologies into education, work, communication, and civic participation has substantially expanded the range of competencies expected of contemporary learners. Digital literacy, digital competence, information literacy, media literacy, technology literacy, computational thinking, data literacy, and more recently AI-related competencies have become increasingly visible alongside the established 4Cs. This expansion reflects a fundamental change in the contexts in which essential competencies are practiced. Communication increasingly occurs through digital platforms, collaboration frequently takes place in technology-mediated environments, creativity involves digital production and innovation, and critical thinking increasingly requires learners to assess the credibility, relevance, reliability, and ethical implications of digitally mediated information.

The relationship between traditional 21st-century competencies and emerging digital competencies is therefore increasingly interconnected. Van Laar et al. (2017) demonstrated substantial overlap between digital skills and broader 21st-century skills, particularly in communication, collaboration, creativity, critical thinking, problem solving, and information management. Their synthesis also identified contextual capabilities such as ethical awareness, cultural awareness, flexibility, self-direction, and lifelong learning, demonstrating that digitally mediated competence extends beyond technical proficiency. Comparative analyses of digital-competence frameworks similarly identify communication, collaboration, information and data handling, content creation, teaching and learning, and ethical dimensions as recurring components (Mattar et al., 2022). In teacher education, digital competence has also become increasingly important not only for effective technology use but also for supporting the development of students' broader competencies (Napal-Fraile et al., 2018).

This convergence is particularly visible in computational and information-related competencies. Computational thinking introduces problem decomposition, abstraction, algorithmic reasoning, and automation into broader problem-solving processes, while remaining conceptually distinguishable from both digital literacy and critical thinking. Research on programming and computational thinking indicates that these activities may simultaneously involve digital competence, cognitive skills, collaboration, language-related capabilities, and creative problem solving (Nouri et al., 2020). Information literacy has also expanded in significance as learners increasingly encounter large volumes of digitally distributed information. It now involves not only locating information but also evaluating source credibility, critically interpreting content, making informed judgments, and navigating issues related to digital security and responsible information use (Banek-Zorica et al., 2025).

These developments indicate that cognitive, interpersonal, informational, technological, and ethical capabilities increasingly operate within overlapping educational environments.

Artificial intelligence has further accelerated this expansion. The growing use of AI and generative AI in teaching, learning, assessment, and educational design introduces additional competency requirements for both students and educators. Teachers increasingly require AI-related digital competencies to integrate emerging technologies effectively into pedagogical practices and to prepare learners for AI-rich environments (Ng et al., 2023). Learners, in turn, are increasingly expected to evaluate AI-generated information, formulate effective interactions with intelligent systems, exercise independent judgment, and retain responsibility for intellectual and ethical decisions. Recent studies have begun connecting AI-supported learning with interdisciplinary STEAM lesson planning, critical thinking, communication, algorithmic reasoning, and digitally mediated creativity (Luo & Tahir, 2025; Zábrádi et al., 2025). These developments do not make the 4Cs obsolete. Instead, they reshape the environments in which critical thinking, creativity, communication, and collaboration are enacted while introducing additional competencies required for critical, responsible, and productive interaction with emerging technologies.

Pedagogical research further demonstrates that these competencies are often developed simultaneously rather than independently. Project-based learning, problem-based learning, inquiry, collaborative learning, STEM and STEAM education, design thinking, game-based learning, makerspaces, immersive environments, and technology-supported learning have frequently been associated with multiple competency outcomes. Project-based learning, for example, has been linked with collaborative learning, problem solving, critical thinking, and learner engagement (Rehman et al., 2024), while STEM-oriented learning commonly integrates disciplinary knowledge with communication, collaboration, creativity, and real-world problem solving (Amri et al., 2024; Papadopoulou et al., 2025). Such approaches provide learning environments in which different competencies may be practiced simultaneously through authentic and collaborative activities.

However, the simultaneous presence of multiple competencies within an instructional approach does not mean that they develop equally. Amri et al. (2024), for example, reported stronger improvement in collaboration than in communication within a STEM-based intervention. Cheng and Weatherly (2025) similarly identified different effect magnitudes across the four Cs in their meta-analysis of digital-game interventions. These differences are theoretically important because they indicate that essential competencies should not be treated as a single undifferentiated construct. Critical thinking, creativity, communication, collaboration, digital literacy, computational thinking, and related capabilities may interact within the same learning environment, but they remain conceptually and empirically distinguishable.

The expanding competency agenda also creates challenges related to assessment and implementation. The conceptual importance attributed to 21st-century skills does not automatically translate into reliable measurement or consistent educational practice. Thornhill-Miller et al. (2023) identify assessment, certification, and institutional promotion as major challenges associated with the 4Cs, while Kayhan and Korkmaz (2024) demonstrate continuing efforts to develop multidimensional instruments for learning and innovation skills. Collaborative problem solving poses additional measurement challenges because it integrates cognitive and social processes that may not be adequately captured through conventional individual assessments. Ioannou et al. (2025) similarly show that makerspaces can provide extensive opportunities for practicing creativity, communication, collaboration, and problem solving even when these competencies are not explicitly assessed. Kamei (2025)

further identifies resource limitations and insufficient teacher preparation as constraints in the implementation and assessment of thinking skills. These concerns indicate that competency research is increasingly moving beyond broad advocacy toward more difficult questions concerning operationalization, measurement, curriculum integration, pedagogical implementation, and transfer.

The development of digital and related competencies is also uneven across educational contexts. Access to infrastructure, institutional support, teacher capability, socioeconomic conditions, and policy environments may substantially influence opportunities for competency development. Ndibalema (2025), for example, identifies inadequate infrastructure, lecturer preparedness, and ICT policy as constraints on the development of digital literacy and broader 21st-century competencies in Sub-Saharan African higher education. Iswatiningsih et al. (2025) similarly report challenges involving digital, visual, and information literacy alongside limitations in infrastructure and teacher preparation. Luengo-Aravena et al. (2024) show that lower levels of digital skill can be associated with socioeconomic disadvantage and weaker experiences of online collaborative problem solving. These findings complicate the assumption that essential-competency frameworks can be implemented uniformly across educational systems and highlight the importance of examining the international distribution and collaborative structure of the research field.

Despite the rapid expansion of scholarship in this area, the knowledge base remains fragmented across competency categories, pedagogical traditions, technologies, disciplines, educational levels, and geographical contexts. Existing reviews have provided valuable insights into specific domains such as digital creativity (Cojocariu & Boghian, 2024), computational thinking and programming (Nouri et al., 2020), digital literacy development (Ndibalema, 2025), collaborative problem solving (Luengo-Aravena et al., 2024), and digital-competence frameworks (Mattar et al., 2022). These contributions clarify important components of contemporary competency research, but they generally examine specific constructs or educational contexts rather than the broader relationships among multiple competency domains.

Bibliometric studies have also emerged in neighboring areas. Prahani et al. (2024) mapped scientific-creativity research and identified assessment, creativity development, and pedagogical strategies as important directions. Yuliana et al. (2025) examined scientific literacy in primary education and highlighted connections among scientific literacy, science education, teacher education, technology, and collaboration. Chamidah et al. (2024) mapped project-based learning and 21st-century-skills research, demonstrating the growing intersection between pedagogy and competency development. Although these studies provide useful representations of particular research areas, their analytical units remain largely subdomain specific. They do not provide an integrated account of how the established 4C framework is structurally and temporally related to digital literacy, digital competence, computational thinking, information literacy, and the wider set of competencies increasingly associated with contemporary education.

This gap has become increasingly important because the conceptual boundaries of the field are difficult to identify through conventional narrative synthesis alone. The literature now spans multiple competency labels, pedagogical approaches, technological environments, disciplines, countries, educational levels, and measurement traditions. The central issue is therefore not simply whether research attention has shifted from one competency label to another. More importantly, it concerns how established and emerging competencies are connected, differentiated, and reorganized within the contemporary educational literature.

A bibliometric approach is appropriate for addressing this problem because it combines performance analysis with science mapping. Performance analysis makes it possible to examine publication productivity, citation impact, and the prominence of authors, sources, institutions, countries, and documents, while science mapping reveals relationships among concepts and contributors through bibliographic networks (Donthu et al., 2021; Zupic & Čater, 2015). Keyword co-occurrence analysis can identify conceptual proximity among competencies, co-authorship analysis can reveal collaborative structures, bibliographic relationships can indicate patterns of scholarly connection, and thematic-evolution analysis can reveal how topics are reorganized across periods. Together, these approaches provide a macro-level representation of a large and heterogeneous research field that would be difficult to obtain through narrative synthesis alone.

Bibliometric evidence nevertheless requires careful interpretation. Network proximity does not demonstrate that one competency causes another, and citation frequency does not establish educational effectiveness or theoretical superiority. Bibliometric clusters are also affected by database coverage, search strategy, metadata quality, keyword normalization, thresholds, and counting procedures (Donthu et al., 2021; Zupic & Čater, 2015). Consequently, bibliometric maps should be interpreted as representations of scholarly structure, conceptual association, research attention, and collaboration rather than direct measurements of learner competence or causal educational mechanisms. This distinction is especially important when considering the relationship between the 4Cs and digital literacy. The growing visibility of digital competencies should not automatically be interpreted as evidence that established competencies have been replaced.

The present study therefore examines the development of research on essential competencies in contemporary education from 2015 to 2025, with particular attention to the relationship between the 4Cs and the expanding digital competency landscape. The central premise is that the field is increasingly characterized by conceptual expansion, differentiation, and recombination. Critical thinking, creativity, communication, and collaboration continue to provide an important conceptual foundation, while digital literacy, digital competence, computational thinking, information literacy, AI-related competencies, pedagogical innovation, assessment, and employability-oriented capabilities increasingly interact with this foundation.

The study contributes to the literature in three principal ways. First, it integrates performance analysis and science mapping across a broad essential-competency domain rather than examining only one skill, technology, or pedagogical approach. Second, it distinguishes publication productivity, citation impact, and network connectivity as different dimensions of scholarly prominence, thereby avoiding the assumption that the most productive contributors are necessarily the most influential or strongly connected. Third, it examines the temporal and conceptual relationships between the established 4C framework and newer digital, informational, computational, and AI-related competencies. This approach makes it possible to determine whether the contemporary knowledge structure is better characterized by replacement, fragmentation, or increasing convergence among competency domains.

Accordingly, the study addresses the following research questions:

- RQ1. How has scholarly production on essential competencies in contemporary education developed between 2015 and 2025, as reflected in publication growth and corpus characteristics?
- RQ2. Which authors, publication sources, institutions, and countries are most prominent in terms of productivity, citation impact, and bibliometric connectivity?

- RQ3. Which highly cited documents have received the greatest scholarly attention, and what major competency agendas do they represent?
- RQ4. What conceptual structure characterizes research on essential competencies in contemporary education?
- RQ5. How are the 4Cs structurally and temporally connected with digital literacy, digital competence, computational thinking, information literacy, and related competency domains?
- RQ6. What thematic developments and emerging research fronts characterize the most recent phase of the field?

METHODS

Data Source and Search Strategy

This study employed a bibliometric design combining performance analysis and science mapping to examine the development and structure of research on essential competencies in contemporary education. Performance analysis was used to characterize publication productivity, citation impact, and the prominence of major research contributors, whereas science mapping was used to examine conceptual, collaborative, and temporal relationships within the field (Donthu et al., 2021; Zupic & Čater, 2015). This analytical distinction was maintained throughout the study to avoid treating productivity, scholarly impact, and network connectivity as equivalent indicators.

Scopus was used as the sole bibliographic database because it provides standardized bibliographic metadata on authors, affiliations, countries, publication sources, citations, keywords, abstracts, and cited references. The use of a single database also ensured consistency in metadata structure across the analytical corpus. Scopus has been widely used in bibliometric studies of related educational research domains and is compatible with analytical environments such as Bibliometrix and VOSviewer (Prahani et al., 2024; Yuliana et al., 2025).

The search was conducted through the title, abstract, and keyword fields using the Scopus TITLE-ABS-KEY function. The retrieval strategy consisted of three conceptual blocks. The first represented the principal competencies examined in the study, including critical thinking, creative thinking, creativity, collaboration, communication skills, digital literacy, digital competence, information literacy, media literacy, and technology literacy. The second restricted retrieval to educational contexts, including education, learning, teaching, school, students, and curriculum. The third required the presence of a broader competency framework represented by terms associated with 4C skills, 21st-century skills, essential competencies, or key competencies. The initial Scopus search expression was:

(TITLE-ABS-KEY (("critical thinking" OR "creative thinking" OR creativity OR collaboration OR "communication skill" OR "digital literacy" OR "digital competenc*" OR "information literacy" OR "media literacy" OR "technology literacy")) AND TITLE-ABS-KEY ((education OR learning OR teaching OR school OR student* OR curriculum)) AND TITLE-ABS-KEY (("4C skill" OR "four C" OR "21st century skill" OR "twenty-first century skill" OR "essential competence" OR "key competence")))*

The competency block ensured that retrieved records addressed at least one substantive competency of interest, while the educational-context block reduced the inclusion of studies in which competency terminology was used exclusively in unrelated professional, technical, clinical, or organizational contexts. The broader competency block maintained the focus on research situated within 4C, 21st-century, essential-competency, or key-competency frameworks.

No subject-area restriction was applied because essential-competency research extends across education, psychology, educational technology, computer science education, STEM and STEAM, language education, vocational education, teacher education, and related interdisciplinary fields. Concepts such as computational thinking, data literacy, AI-related competence, digital transformation, and robotics were not imposed as mandatory retrieval terms. When these concepts occurred within eligible records, their presence and relationships were identified through subsequent keyword and thematic analyses rather than predetermined by the search strategy.

Bibliographic metadata were exported from Scopus on 12 August 2026 in CSV-compatible format. The exported records contained, where available, authors and author identifiers, affiliations, titles, abstracts, author keywords, index keywords, source titles, publication years, citation counts, cited references, DOI information, document type, and other bibliographic metadata required for the analyses.

Eligibility Criteria and Dataset Finalization

Dataset construction followed a three-stage retrieval and refinement procedure. In the first stage, the initial topic-based query identified 2,530 Scopus-indexed records. In the second stage, the publication period was restricted to 2015–2025 by applying the conditions PUBYEAR > 2014 and PUBYEAR < 2026, reducing the dataset to 2,158 records. In the third stage, the search was restricted to English-language publications, while notes, errata, data papers, retracted publications, and editorials were excluded. These refinements produced a final analytical corpus of 2,070 documents. The final filtering conditions incorporated the following restrictions:

(EXCLUDE (DOCTYPE, "dp") OR EXCLUDE (DOCTYPE, "er") OR EXCLUDE (DOCTYPE, "no") OR EXCLUDE (DOCTYPE, "tb") OR EXCLUDE (DOCTYPE, "ed")) AND (LIMIT-TO (LANGUAGE, "English")) AND PUBYEAR > 2014 AND PUBYEAR < 2026

Figure 1 summarizes the complete Scopus identification and refinement process.

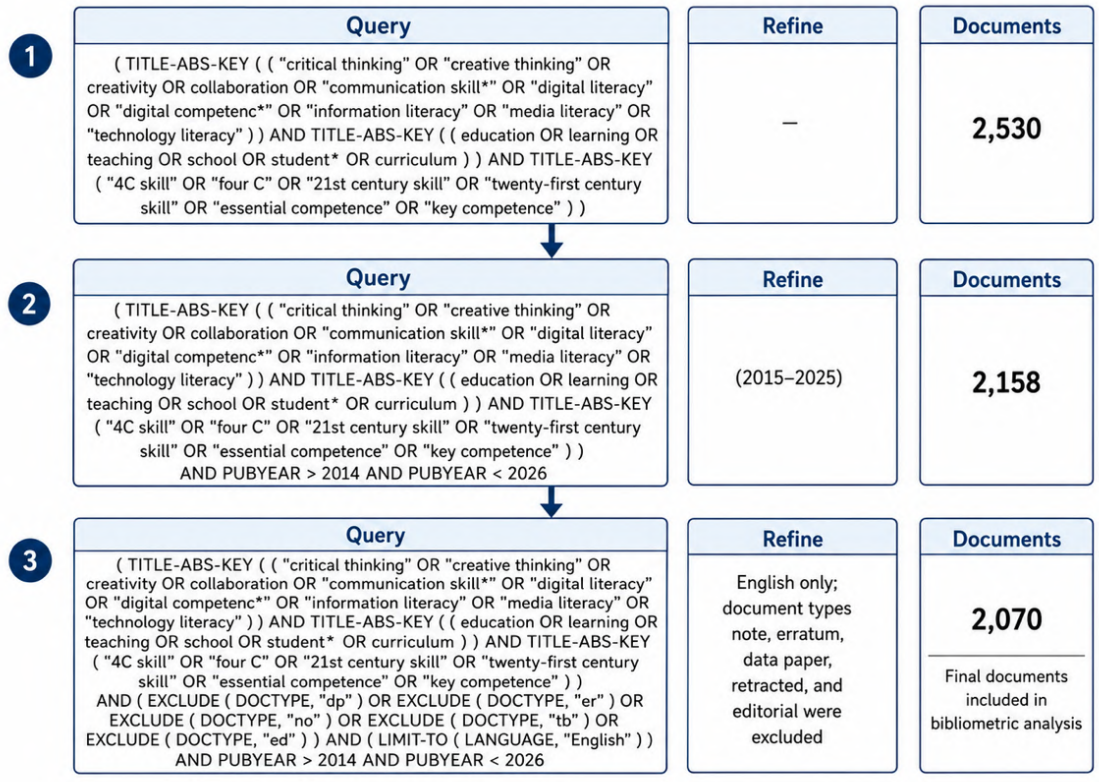


Figure 1. Scopus dataset identification and refinement process

Eligibility was operationalized through the search terms and database filters. Records were retained when they simultaneously represented an educational or learning context, were situated within a broader 4C, 21st-century, essential-competency, or key-competency framework, and addressed at least one substantive competency included in the retrieval strategy. Publications outside the 2015–2025 period, non-English publications, and the specified excluded document types were not retained.

The final dataset comprised 1,138 journal articles, 580 conference papers, 243 book chapters, 76 reviews, 25 books, and 8 conference reviews, yielding a total of 2,070 documents. Because Scopus was the sole bibliographic database, cross-database deduplication was not required. The resulting corpus was used consistently for descriptive bibliometric analysis, contributor analysis, network mapping, and thematic analysis.

Data Cleaning and Preprocessing

Data preprocessing was conducted to improve metadata consistency while preserving meaningful conceptual distinctions among competency constructs. This procedure was particularly important because several concepts within the field are closely related but not theoretically equivalent. Digital literacy, digital competence, computational thinking, critical thinking, information literacy, media literacy, and technology literacy were therefore retained as distinguishable constructs unless differences were clearly attributable to orthographic or grammatical variation.

Author identification relied primarily on author information and identifiers available in Scopus. Clear naming variants were reviewed to reduce unnecessary fragmentation of publication output across obviously equivalent records. Affiliation and country labels were standardized at the reporting stage to ensure consistency in institutional and national names. Extensive manual reassignment of authors was avoided when the available metadata did not provide sufficient evidence for unambiguous identification. Incomplete or uncertain metadata were therefore retained cautiously rather than reassigned without verification.

Keyword normalization followed a conservative approach. Clear orthographic and formatting variants were reviewed, including differences associated with hyphenation and closely equivalent grammatical forms, such as problem solving/problem-solving, decision making/decision-making, and digital competence/digital competency. Related but conceptually distinct constructs were not automatically merged. Digital literacy was not combined with computational thinking, critical thinking was not treated as equivalent to higher-order thinking skills, and information literacy, media literacy, technology literacy, and digital competence remained analytically distinguishable.

This approach preserved conceptual variation within the bibliometric network. The proximity or co-occurrence of terms was interpreted as evidence of bibliographic association rather than theoretical equivalence. Retaining related constructs as separate items therefore made it possible to examine how different competencies were positioned in relation to one another.

Generic educational terms were not automatically removed when they provided substantive information about the contexts in which competencies were studied. Terms such as higher education, teaching, learning, and professional development were retained when they contributed to the interpretation of educational settings. The interpretation nevertheless emphasized substantively meaningful competency and pedagogical terms rather than relying on generic metadata labels alone.

A second stage of preprocessing involved substantive inspection of representative bibliographic records. Titles, abstracts, keywords, publication sources, and document types

were examined to support the interpretation of major competency areas and reduce reliance on network position alone. This process was particularly relevant to the interpretation of leading contributors, highly cited documents, major thematic structures, and emerging competency areas. Data preprocessing therefore served two complementary purposes: improving bibliographic consistency for quantitative analysis and providing substantive context for interpretation of the resulting bibliometric structures.

Bibliometric Analysis

The analytical framework consisted of two complementary components: performance analysis and science mapping. Performance analysis focused on the productivity and scholarly visibility of research constituents, whereas science mapping examined relationships among concepts, countries, publication sources, and documents (Donthu et al., 2021; Zupic & Čater, 2015).

Performance Analysis

Descriptive bibliometric analysis was conducted in R version 4.4.0 using the Bibliometrix environment (Aria & Cuccurullo, 2017). Dataset-level indicators included the number of documents, publication sources, authors, cited references, author keywords, index keywords, annual growth rate, average document age, average citations per document, single-authored documents, co-authors per document, international co-authorship percentage, and document-type distribution.

Contributor analysis examined the leading authors, publication sources, institutions, and countries. Publication count was used as the principal productivity indicator, while citation counts represented accumulated scholarly attention. Network-related measures, including total link strength, were used where relevant to characterize connectivity within the corresponding bibliometric network. Productivity, citation impact, and network connectivity were treated as distinct dimensions rather than interchangeable indicators of scholarly prominence.

The ten most highly cited documents were identified according to total Scopus citation counts. Their titles, abstracts, keywords, and bibliographic metadata were subsequently examined to identify the main competency agendas represented by highly visible publications. No minimum document or citation threshold was imposed for the descriptive top-ten rankings because the purpose was to identify the highest-ranked entities rather than construct threshold-dependent networks. Citation totals were interpreted as indicators of accumulated scholarly attention within Scopus rather than direct measures of methodological quality, theoretical validity, or educational effectiveness.

Science Mapping

Network construction and visualization were conducted using VOSviewer version 1.6.20 (van Eck & Waltman, 2010). Full counting was applied to the VOSviewer network analyses. Under this approach, each occurrence or collaborative contribution receives full weight rather than being fractionally distributed among participating authors, countries, or other bibliometric entities.

Keyword co-occurrence analysis was used to investigate the conceptual structure of the field. A minimum occurrence threshold of five was applied to the keyword metadata available in the Scopus corpus, and terms meeting this threshold were included in the network analysis. Three complementary visualizations were generated. The network visualization was used to examine conceptual proximity and connections among major competency terms; the overlay

visualization was used to examine their relative temporal positions; and the density visualization was used to identify areas of greater thematic concentration.

These visualizations were interpreted jointly rather than as independent measures of conceptual importance. Node prominence and proximity were used to characterize the structure of relationships among concepts, while temporal position and density provided complementary information about the development and concentration of research attention. Co-occurrence was interpreted as evidence that concepts were discussed together within the literature and not as evidence that one competency caused, produced, or was theoretically equivalent to another.

Country co-authorship analysis was also conducted using full counting. Publication counts, citation totals, and total link strength were considered jointly when interpreting national research patterns. Total link strength in the country network was interpreted specifically as an indicator of collaboration connectivity within that network and was not compared directly with total link strength generated from other bibliometric relationships.

Bibliographic coupling was used as a supplementary relational indicator for selected publication sources and documents. Corresponding total link strength values were used, where available, to characterize the extent of shared bibliographic connections. Because total link strength is dependent on the type of network being analyzed, values were interpreted only within their respective bibliometric relations and were not treated as directly comparable across co-authorship, keyword co-occurrence, or bibliographic-coupling networks.

Thematic Evolution and Time-Slice Analysis

The temporal development of the field was examined using thematic-evolution analysis in the R/Bibliometrix environment. The corpus was divided into four analytical periods: 2015–2020, 2021–2022, 2023–2024, and 2025. These periods were used consistently in the thematic-evolution and strategic-diagram analyses. The thematic-evolution map was used to examine continuity, differentiation, and changing connections among topics across successive periods, while the strategic thematic diagrams were interpreted according to centrality and density, producing four conventional thematic positions: motor themes, niche themes, basic themes, and emerging or declining themes (Aria & Cuccurullo, 2017).

The interpretation of the emerging or declining quadrant was treated cautiously because its position may represent either themes beginning to gain structural relevance or themes losing prominence. Temporal position alone was therefore not considered sufficient evidence that a topic represented an emerging research front. Interpretation was supported by its continuity across periods, position within the broader keyword structure, and substantive relationship with representative publications.

The higher-order thematic domains used to synthesize the field were not treated as fixed software-generated clusters. Instead, they were derived through interpretive integration of keyword co-occurrence, overlay and density visualization, thematic evolution, time-slice strategic diagrams, highly cited publications, source profiles, and examination of representative bibliographic records. The resulting domains comprised: (1) 4C skills and core 21st-century competencies; (2) digital literacy, digital competence, and technology-supported learning; (3) pedagogical models and innovative learning strategies; (4) assessment, measurement, and learning outcomes; and (5) collaboration, problem solving, computational thinking, and STEM/STEAM. Smaller or less consolidated topics were considered separately when the temporal and conceptual evidence indicated their relevance as minor or emerging themes.

Bibliometric clusters and thematic positions were treated as empirical representations conditional on the selected database, search strategy, preprocessing decisions, counting method, occurrence threshold, and analytical settings. No alternative keyword thresholds, fractional-counting procedures, or formal sensitivity analyses were conducted. Consequently, the resulting maps were interpreted as representations of publication activity, scholarly attention, conceptual proximity, thematic development, and collaboration within the defined Scopus corpus rather than as evidence of causal relationships or comparative educational effectiveness.

RESULTS AND DISCUSSION

Dataset Characteristics and Publication Profile

Table 1 summarizes the principal characteristics of the bibliometric dataset used to examine research on essential competencies in contemporary education from 2015 to 2025. The table provides information on the size and composition of the corpus, publication growth, citation characteristics, bibliographic references, keyword metadata, authorship patterns, international collaboration, and document types. These indicators establish the empirical profile of the dataset before the analysis proceeds to leading contributors, citation patterns, conceptual networks, international collaboration, and thematic development.

Table 1. Dataset characteristics

Description	Result
Timespan	2015–2025
Sources	965
Documents	2,070
Annual growth rate (%)	19.72
Average document age	4.44
Average citations per document	14.17
References	161,002
Index keywords	3,802
Author keywords	4,470
Authors	5,714
Authors of single-authored documents	305
Single-authored documents	323
Co-authors per document	3.2
International co-authorship (%)	15.8
Articles	1,138
Conference papers	580
Book chapters	243
Reviews	76
Books	25
Conference reviews	8

As shown in Table 1, the final corpus comprised 2,070 documents distributed across 965 publication sources and involving 5,714 authors. The records collectively contained 161,002 cited references, 4,470 author keywords, and 3,802 index keywords. The annual publication growth rate was 19.72%, while the average document age was 4.44 years and the mean citation rate was 14.17 citations per document. Together, these indicators show substantial expansion in publication activity and considerable dispersion of the literature across a broad range of scholarly outlets.

The document distribution was dominated by journal articles, which accounted for 1,138 records or approximately 55.0% of the corpus. Conference papers represented 580 records or 28.0%, followed by 243 book chapters, 76 reviews, 25 books, and 8 conference reviews. Authorship was predominantly collaborative, with 323 single-authored documents and an average of 3.2 co-authors per publication. Internationally co-authored documents accounted for 15.8% of the dataset, showing that collaborative publication was common overall, although cross-national collaboration represented a smaller component of total scholarly production.

The annual growth rate provides evidence of overall expansion across the 2015–2025 study period, but the available bibliometric summary does not provide publication counts for every individual year. Consequently, the results support conclusions regarding aggregate growth rather than specific annual phases of expansion. The available evidence therefore does not justify attributing particular increases in publication activity to specific external events such as pandemic-related online learning, curriculum reform, accelerated digitalization, or the emergence of generative artificial intelligence.

Leading Contributors and Scholarly Influence

Table 2 integrates the principal bibliometric indicators for leading authors, publication sources, institutions, countries, and highly cited documents. Rather than functioning as a single ranking, the table distinguishes publication productivity, citation impact, network-related connectivity, and substantive competency focus. This structure makes it possible to identify differences between entities that produce a large number of publications, entities that receive substantial scholarly attention, and entities that occupy strongly connected positions within the relevant bibliometric networks while simultaneously showing the competency areas associated with each contributor.

Table 2. Top contributors and competency profiles in essential-competency research

Category	Contributor / Item	Productivity / Document Information	Impact Indicator	Collaboration / Link Indicator	Main Competency Focus
Author	Wibowo FC	Document count: 8	Citations: 55	TLS: 28	Educational technology applications
Author	Zubaidah S	Document count: 8	Citations: 35	TLS: 305	Critical-thinking development in diverse educational contexts
Author	Jr	Document count: 7	Citations: 30	TLS: 76	Learning innovations
Author	Prahani BK	Document count: 7	Citations: 110	TLS: 113	Innovative learning models for physics education
Author	Rahmawati Y	Document count: 7	Citations: 147	TLS: 221	Interdisciplinary approaches in STEM education
Author	Saputro S	Document count: 7	Citations: 44	TLS: 76	Critical-thinking development in diverse educational contexts
Author	Susilo H	Document count: 7	Citations: 34	TLS: 198	Critical-thinking development in

Category	Contributor / Item	Productivity / Document Information	Impact Indicator	Collaboration / Link Indicator	Main Competency Focus
					diverse educational contexts
Author	Awwal N	Document count: 6	Citations: 55	TLS: 245	Collaborative problem solving in learning environments
Author	Chu SKW	Document count: 6	Citations: 889	TLS: 1,498	AI and machine learning in educational design
Author	Drachsler H	Document count: 6	Citations: 235	TLS: 161	Learning analytics in e-learning environments
Source / Journal	Journal of Physics: Conference Series	Document count: 77	Citations: 456	Bibliographic-coupling TLS: 137	STEM-based science, physics, and mathematics learning; teacher education; 4C skills; critical thinking; creativity; communication; collaboration; problem solving; digital and scientific literacy; HOTS; learning outcomes
Source / Journal	AIP Conference Proceedings	Document count: 72	Citations: 185	Bibliographic-coupling TLS: 328	STEM/STEAM; project-based and problem-based learning; digital learning; science and mathematics education; 4Cs; technological and scientific literacy; assessment
Source / Journal	Thinking Skills and Creativity	Document count: 42	Citations: 1,471	Bibliographic-coupling TLS: 1,037	Higher-order thinking; creativity; critical thinking; design thinking; metacognition; computational thinking; problem solving; collaboration; communication; competency assessment

Category	Contributor / Item	Productivity / Document Information	Impact Indicator	Collaboration / Link Indicator	Main Competency Focus
Source / Journal	ACM International Conference Proceeding Series	Document count: 31	Citations: 190	Bibliographic-coupling TLS: 159	Digital competence; computer science education; learning analytics; makerspaces; collaborative learning; problem-based/project-based learning; ICT literacy; teamwork; self-directed learning; assessment
Source / Journal	Lecture Notes in Networks and Systems	Document count: 30	Citations: 42	Bibliographic-coupling TLS: 66	AI-supported education; digital transformation; design thinking; engineering education; robotics; data literacy; immersive learning; systems thinking; employability; leadership; career readiness
Source / Journal	Sustainability (Switzerland)	Document count: 28	Citations: 806	Bibliographic-coupling TLS: 173	Sustainability education; teacher education; STEM/STEAM; digital/mobile learning; 4Cs; digital/information/ media literacy; sustainability competence; lifelong learning; employability
Source / Journal	Proceedings of the European Conference on Games-Based Learning	Document count: 27	Citations: 102	Bibliographic-coupling TLS: 249	Game-based learning; serious games; gamification; VR/AR; decision making; computational thinking; socio-emotional competence; 4C development
Source / Journal	Education Sciences	Document count: 26	Citations: 583	Bibliographic-coupling TLS: 207	Digital creativity; digital competence; STEM/STEAM;

Category	Contributor / Item	Productivity / Document Information	Impact Indicator	Collaboration / Link Indicator	Main Competency Focus
					computational thinking; project-based learning; design thinking; teacher education; metacognition; assessment
Source / Journal	Frontiers in Education	Document count: 25	Citations: 498	Bibliographic-coupling TLS: 203	Digital literacy; critical online reasoning; STEM; design thinking; educational robotics; gamification; collaborative problem solving; socio-emotional skills; employability
Source / Journal	International Journal of Learning, Teaching and Educational Research	Document count: 22	Citations: 110	Bibliographic-coupling TLS: 379	Teacher education; blended/problem-based learning; project-based and inquiry learning; STEM; EFL; TVET; digital literacy; computational thinking; multicultural competence; learning outcomes
Institution	Universitas Pendidikan Indonesia	Publications: 103	Citations: 302	Co-authorship TLS: 1	STEM/Education 5.0; e-learning; project-based learning; design thinking; critical thinking; creativity; collaboration; communication; digital literacy; problem solving
Institution	Universitas Negeri Malang	Publications: 101	Citations: 208	Co-authorship TLS: 0	Innovative pedagogy and competency-based learning; 4Cs; digital literacy; problem solving; learning outcomes

Category	Contributor / Item	Productivity / Document Information	Impact Indicator	Collaboration / Link Indicator	Main Competency Focus
Institution	Universitas Negeri Padang	Publications: 75	Citations: 225	Co-authorship TLS: 0	Pedagogical and technology-supported competency development; 4Cs; digital literacy; problem solving; learning outcomes
Institution	Universitas Negeri Yogyakarta	Publications: 57	Citations: 259	Co-authorship TLS: 0	Critical thinking; creative thinking; problem solving; curriculum integration; learning models; 21st-century skills
Institution	Universitas Negeri Jakarta	Publications: 45	Citations: 273	Co-authorship TLS: 0	Competency-based and technology-supported learning; 4Cs; digital literacy; teacher education; problem solving
Institution	Universitas Negeri Surabaya	Publications: 42	Citations: 283	Co-authorship TLS: 0	Innovative learning; 4Cs; digital literacy; problem solving; STEM/STEAM; learning outcomes
Institution	The University of Hong Kong	Publications: 40	Citations: 1,327	Co-authorship TLS: 10	Digital literacy; communication; collaboration; critical thinking; creativity; problem solving; language learning; learning analytics; assessment
Institution	Universitas Sebelas Maret	Publications: 40	Citations: 217	Co-authorship TLS: 0	Technology-supported and competency-based learning; 4Cs; digital literacy; STEM/STEAM; teacher education
Institution	Universitas Negeri Semarang	Publications: 35	Citations: 31	Co-authorship TLS: 0	Competency-based and innovative pedagogy; 4Cs; digital literacy; STEM/STEAM; teacher education

Category	Contributor / Item	Productivity / Document Information	Impact Indicator	Collaboration / Link Indicator	Main Competency Focus
Institution	University of Oulu	Publications: 28	Citations: 893	Co-authorship TLS: 0	Digital literacy; computational thinking; collaboration; communication; problem solving; learning analytics; teacher education
Country	Indonesia	Publications: 263	Citations: 1,349	International collaboration TLS: 10,777	STEM/STEAM; science and mathematics education; blended PBL; ethnoscience; Merdeka Curriculum; teacher and vocational education; multiliteracy; ICT-supported learning; 4Cs; scientific literacy
Country	United States	Publications: 117	Citations: 3,300	International collaboration TLS: 16,225	STEM identity; maker education; visual/media literacy; connected learning; professional development; 4Cs; digital/information literacy; entrepreneurship; assessment; workplace readiness
Country	Turkey	Publications: 77	Citations: 1,179	International collaboration TLS: 7,346	Teacher competence; digital and visual literacy; robotics; coding; STEM; social-media learning; 4Cs; digital citizenship; digital ethics
Country	Spain	Publications: 66	Citations: 1,249	International collaboration TLS: 5,061	Digital competence; flipped classroom; vocational and technical education; STE(A)M/CLIL; engineering PBL; 4Cs; ICT skills; self-assessment

Category	Contributor / Item	Productivity / Document Information	Impact Indicator	Collaboration / Link Indicator	Main Competency Focus
Country	China	Publications: 63	Citations: 1,336	International collaboration TLS: 6,570	Design education; self-directed learning; creativity; collaboration assessment; digital media production; gamification; scenario planning; 4C skills; data-driven assessment
Country	Malaysia	Publications: 55	Citations: 565	International collaboration TLS: 5,530	STEAM; ESL teacher education; digital literacy; mobile/online/hybrid learning; 4Cs; PBL; digital game-based learning
Country	Australia	Publications: 53	Citations: 844	International collaboration TLS: 8,018	Collaborative problem solving; creativity; scenario planning; leadership; communication; critical thinking; work readiness
Country	Germany	Publications: 43	Citations: 867	International collaboration TLS: 8,977	Critical-thinking assessment; computational thinking; mathematical modelling; complex problem solving; decision making; metacognition; performance assessment
Country	Netherlands	Publications: 36	Citations: 2,232	International collaboration TLS: 4,754	Boundary crossing; interdisciplinary/transdisciplinary learning; co-design; collaboration; creativity; empathy; formative assessment; computational thinking; multimodal analytics

Category	Contributor / Item	Productivity / Document Information	Impact Indicator	Collaboration / Link Indicator	Main Competency Focus
Country	Thailand	Publications: 34	Citations: 136	International collaboration TLS: 1,450	Project-based learning; virtual/flipped learning; ASEAN collaboration; computational thinking; STEM leadership; AR serious games; digital/information/ media literacy; adaptability
Highly cited document	van Laar et al. (2017)	The relation between 21st-century skills and digital skills: A systematic literature review	Citations: 1,449	Bibliographic-coupling TLS: 6	Digital and 21st-century skills; information management; communication; collaboration; creativity; critical thinking; problem solving; ethical awareness; flexibility; self-direction; lifelong learning
Highly cited document	Ng et al. (2023)	Teachers' AI digital competencies and twenty-first century skills in the post-pandemic world	Citations: 528	Bibliographic-coupling TLS: 3	Teacher AI literacy; AI digital competence; digital teaching; AI-enhanced learning; assessment; 21st-century skills
Highly cited document	Thornhill-Miller et al. (2023)	Creativity, Critical Thinking, Communication, and Collaboration: Assessment, Certification, and Promotion of 21st Century Skills for the Future of Work and Education	Citations: 508	Bibliographic-coupling TLS: 5	Assessment and certification of the 4Cs; soft skills; future-work readiness; educational training; AI; VR
Highly cited document	Papanastasiou et al. (2019)	Virtual and augmented reality effects on K-12, higher and tertiary education	Citations: 396	Bibliographic-coupling TLS: 2	VR/AR; digital-age literacy; creative thinking; communication; collaboration;

Category	Contributor / Item	Productivity / Document Information	Impact Indicator	Collaboration / Link Indicator	Main Competency Focus
		students' twenty-first century skills			problem solving; spatial ability; engagement
Highly cited document	Konttila et al. (2019)	Healthcare professionals' competence in digitalisation: A systematic review	Citations: 344	Bibliographic-coupling TLS: 0	Professional digital competence; digital technology knowledge; communication; ethical competence; organizational support; workplace readiness
Highly cited document	Rios et al. (2020)	Identifying Critical 21st-Century Skills for Workplace Success: A Content Analysis of Job Advertisements	Citations: 287	Bibliographic-coupling TLS: 0	Communication; collaboration; problem solving; critical thinking; employability-related skill demand
Highly cited document	Nouri et al. (2020)	Development of computational thinking, digital competence and 21st century skills when learning programming in K-9	Citations: 279	Bibliographic-coupling TLS: 5	Programming; computational thinking; digital competence; collaboration; cognitive skills; language skills; creative problem solving
Highly cited document	Chu et al. (2017)	21st century skills development through inquiry-based learning: From theory to practice	Citations: 264	Bibliographic-coupling TLS: 6	Inquiry/project-based learning; critical thinking; collaboration; student agency; knowledge building; digital-tool use
Highly cited document	Stehle and Peters-Burton (2019)	Developing student 21st Century skills in selected exemplary inclusive STEM high schools	Citations: 247	Bibliographic-coupling TLS: 1	STEM education; collaboration; knowledge construction; real-world problem solving; self-regulation; communication; technology-supported learning

Category	Contributor / Item	Productivity / Document Information	Impact Indicator	Collaboration / Link Indicator	Main Competency Focus
Highly cited document	Kostka and Toncelli (2023)	Exploring Applications of ChatGPT to English Language Teaching: Opportunities, Challenges, and Recommendations	Citations: 211	Bibliographic-coupling TLS: 0	Generative AI; ChatGPT; human-machine collaboration; pedagogical innovation; AI literacy; language learning; responsible AI use

Table 2 shows that publication productivity, citation impact, and bibliometric connectivity produced different patterns across contributor categories. Wibowo FC and Zubaidah S recorded the largest publication counts among the leading authors, whereas Chu SKW showed considerably greater citation impact and TLS. At the source level, Journal of Physics: Conference Series and AIP Conference Proceedings led in publication volume, while Thinking Skills and Creativity showed substantially greater citation visibility and bibliographic-coupling strength despite publishing fewer documents. This distinction confirms that different indicators capture different forms of prominence within the corpus.

A comparable pattern appeared at institutional and national levels. Indonesian universities dominated publication output, particularly Universitas Pendidikan Indonesia and Universitas Negeri Malang, whereas The University of Hong Kong and University of Oulu accumulated relatively high citation totals despite smaller publication volumes. Indonesia was the most productive country, while the United States recorded the highest citation count and international collaboration TLS among the leading countries. The Netherlands also exhibited high citation visibility relative to its comparatively modest publication output.

Leading Authors

The author-level analysis revealed a dispersed productivity structure. Wibowo FC and Zubaidah S each produced eight documents, while Prahani BK, Rahmawati Y, Saputro S, Susilo H, and the unresolved "Jr" entry each produced seven. Among authors with six publications, Chu SKW recorded 889 citations and a TLS of 1,498, substantially higher than the corresponding values of the other highly productive authors. Drachsler H accumulated 235 citations and a TLS of 161, while Awwal N recorded 55 citations and a TLS of 245.

The competency profiles associated with these authors were heterogeneous. Wibowo FC was linked primarily to educational technology applications, while Zubaidah S, Saputro S, and Susilo H were associated with critical-thinking development. Prahani BK was linked to innovative learning models in physics education, Rahmawati Y to interdisciplinary STEM approaches, Awwal N to collaborative problem solving, Chu SKW to AI and machine learning in educational design, and Drachsler H to learning analytics and e-learning. The "Jr" entry was retained descriptively but not interpreted further because its complete identity could not be reliably established.

Leading Publication Sources

The source-level results indicate that research on essential competencies was distributed across conference-oriented STEM outlets, specialist thinking-skills journals, educational technology publications, sustainability journals, and general education sources. Journal of

Physics: Conference Series was the most productive outlet with 77 documents, followed by AIP Conference Proceedings with 72. Both sources showed strong representation of STEM/STEAM, science and mathematics education, project-based learning, problem-based learning, digital learning, critical thinking, creativity, communication, collaboration, problem solving, digital literacy, and learning outcomes.

Thinking Skills and Creativity displayed a different bibliometric profile, contributing 42 documents while accumulating 1,471 citations and a bibliographic-coupling TLS of 1,037. Its publications emphasized creativity, critical thinking, higher-order thinking, design thinking, metacognition, computational thinking, problem solving, collaboration, communication, and assessment. Other leading sources broadened the thematic landscape toward AI-supported education, digital transformation, robotics, sustainability, game-based learning, immersive technologies, learning analytics, teacher education, digital competence, socio-emotional skills, and employability.

Leading Institutions

Institutional publication activity was strongly concentrated among Indonesian universities. Universitas Pendidikan Indonesia produced 103 publications, Universitas Negeri Malang 101, and Universitas Negeri Padang 75, with several other Indonesian institutions also appearing among the ten leading contributors. Their competency profiles included STEM/STEAM, innovative pedagogy, project-based learning, critical thinking, creativity, communication, collaboration, digital literacy, problem solving, teacher education, curriculum integration, and learning outcomes, showing substantial institutional engagement with competency-oriented teaching and learning research.

Citation visibility differed considerably from publication volume. The University of Hong Kong produced 40 documents but accumulated 1,327 citations, whereas the University of Oulu produced 28 documents and accumulated 893 citations. The University of Hong Kong was associated with digital literacy, communication, collaboration, critical thinking, creativity, language learning, learning analytics, and assessment. The University of Oulu was particularly associated with digital literacy, computational thinking, collaboration, communication, problem solving, learning analytics, teacher education, and technology-supported learning.

Country Productivity, Impact, and International Collaboration

Indonesia recorded the highest publication output with 263 publications, followed by the United States with 117, Turkey with 77, Spain with 66, and China with 63. Malaysia, Australia, Germany, the Netherlands, and Thailand were also represented among the leading national contributors. Indonesian research showed a broad profile involving STEM/STEAM, science and mathematics education, blended problem-based learning, ethnoscience, the Merdeka Curriculum, teacher and vocational education, multiliteracy, ICT-supported learning, the 4Cs, scientific literacy, and learning outcomes.

The United States accumulated 3,300 citations and recorded an international collaboration TLS of 16,225, the highest values among the leading countries for these indicators. The Netherlands accumulated 2,232 citations from 36 publications, while Germany recorded an international collaboration TLS of 8,977 from 43 publications. National research profiles also differed substantively, ranging from digital citizenship and robotics in Turkey to digital competence and vocational education in Spain, computational and assessment research in Germany, and interdisciplinary learning and multimodal analytics in the Netherlands.

Highly Cited Documents

The highly cited documents reveal several publications that received substantial scholarly attention within the corpus and connect established 21st-century competencies with newer digitally mediated competency areas. Van Laar et al. (2017) was the most highly cited publication with 1,449 citations, followed by Ng et al. (2023) with 528 and Thornhill-Miller et al. (2023) with 508. These studies respectively linked digital and 21st-century skills, extended teacher competence toward AI literacy and AI-supported learning, and addressed assessment and institutional promotion of the 4Cs.

The remaining highly cited publications broadened the field toward immersive technologies, healthcare digital competence, workplace readiness, programming, inquiry learning, STEM education, and generative AI. Papanastasiou et al. examined VR and AR, Konttila et al. focused on professional digital competence, Rios et al. addressed workplace-oriented competencies, Nouri et al. linked programming with computational thinking, Chu et al. examined inquiry-based learning, Stehle and Peters-Burton addressed inclusive STEM schools, and Kostka and Toncelli connected ChatGPT with human-machine collaboration, language learning, and AI literacy.

Conceptual Structure of Essential-Competency Research

Keyword Co-occurrence Network

Figure 2 presents the keyword co-occurrence network and provides the principal representation of conceptual relationships among recurring terms in the corpus. The visualization makes it possible to examine the prominence, proximity, and connections among 21st-century skills, the 4Cs, digital competencies, computational concepts, information-related competencies, pedagogical approaches, and educational contexts. Particular attention is directed toward 21st-century skills, creativity, collaboration, critical thinking, digital literacy, computational thinking, and information literacy because these concepts are directly related to the central questions of the study.

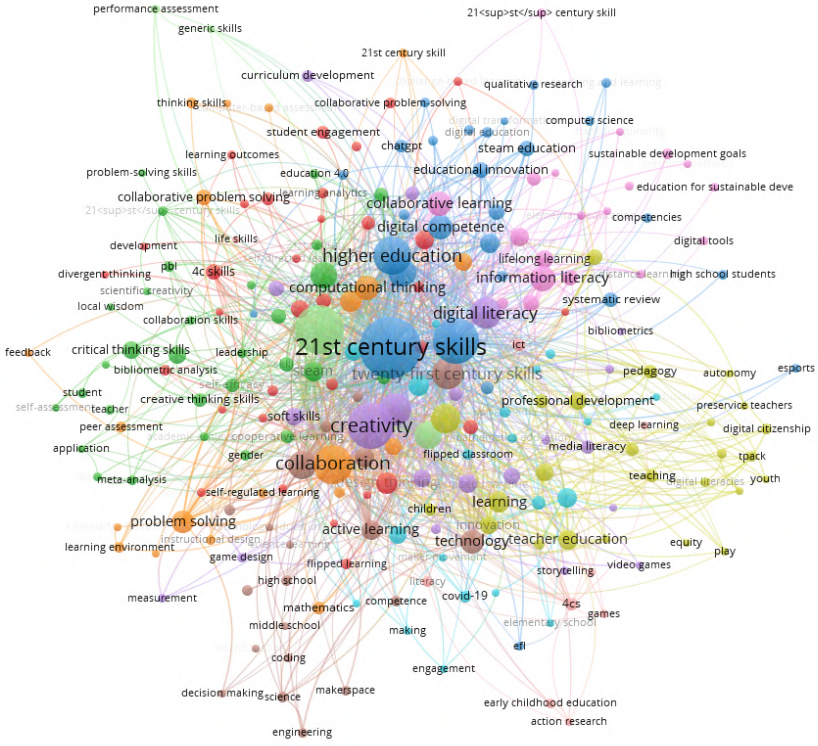


Figure 2. Keyword co-occurrence network

Figure 2 shows that "21st century skills" formed the most visually prominent and centrally positioned term in the network. Creativity, collaboration, digital literacy, critical thinking skills, computational thinking, information literacy, higher education, collaborative learning, problem solving, active learning, technology, and learning were positioned within or close to the central structure. The relative proximity of these terms demonstrates that established 4C-related concepts and digitally oriented competencies occurred within a common bibliometric space rather than forming two disconnected conceptual regions.

The network also included pedagogical and contextual terms such as problem-based learning, active learning, flipped classroom, collaborative learning, STEM education, educational innovation, game design, professional development, learning analytics, and technology-supported education. Their proximity to competency-related nodes shows that essential competencies were frequently examined in relation to specific instructional models and educational environments. More peripheral terms included digital citizenship, autonomy, esports, games, coding, decision making, makerspaces, early childhood education, and performance assessment, indicating smaller or more specialized strands within the wider conceptual structure.

Temporal Overlay

Figure 3 presents the keyword overlay visualization and adds a temporal dimension to the structural relationships shown in Figure 2. The map enables comparison of the relative temporal positions of major and specialized concepts within the same bibliometric network rather than dividing the literature into completely independent chronological stages. This visualization is particularly relevant for examining whether digital and technology-related concepts became relatively more recent while established competencies such as critical thinking, creativity, communication, collaboration, and broader 21st-century skills remained visible across the study period.

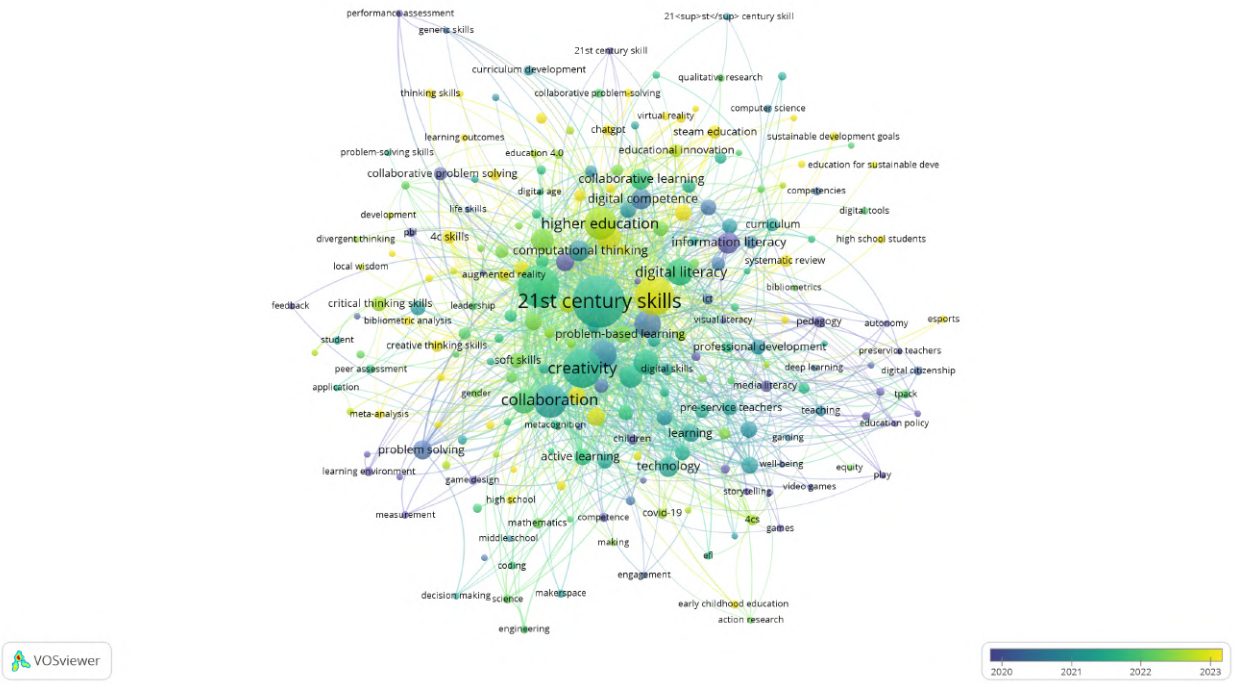


Figure 3. Keyword overlay visualization

As shown in Figure 3, 21st-century skills, creativity, collaboration, digital literacy, higher education, learning, and computational thinking remained highly visible within the

overlay network. At the same time, digital competence, information literacy, educational innovation, professional development, digital tools, and technology-supported education occupied relatively more recent positions. The distribution indicates increasing visibility of specialized digital and technology-oriented terminology within an established research structure that continued to contain cognitive, interpersonal, pedagogical, and educational-context concepts.

The temporal pattern does not show disappearance of the established 4C-related terms as newer digital concepts become more visible. Instead, established and more recent terms occupy overlapping areas of the same network, with differences primarily evident in their relative temporal positions. At the descriptive bibliometric level, the evidence therefore indicates broadening and differentiation of the competency landscape rather than a simple sequential replacement of established competencies by digital literacy or digital competence.

Keyword Density

Figure 4 presents the keyword density visualization and complements the network and overlay maps by identifying areas where recurring terms were most strongly concentrated. Whereas Figure 2 emphasizes relationships among terms and Figure 3 adds information about their relative temporal position, Figure 4 shows areas of greater and lower bibliometric concentration. This representation therefore provides an additional perspective for identifying the conceptual core of the literature and differentiating it from smaller, more specialized research areas without treating density itself as evidence of theoretical or educational importance.

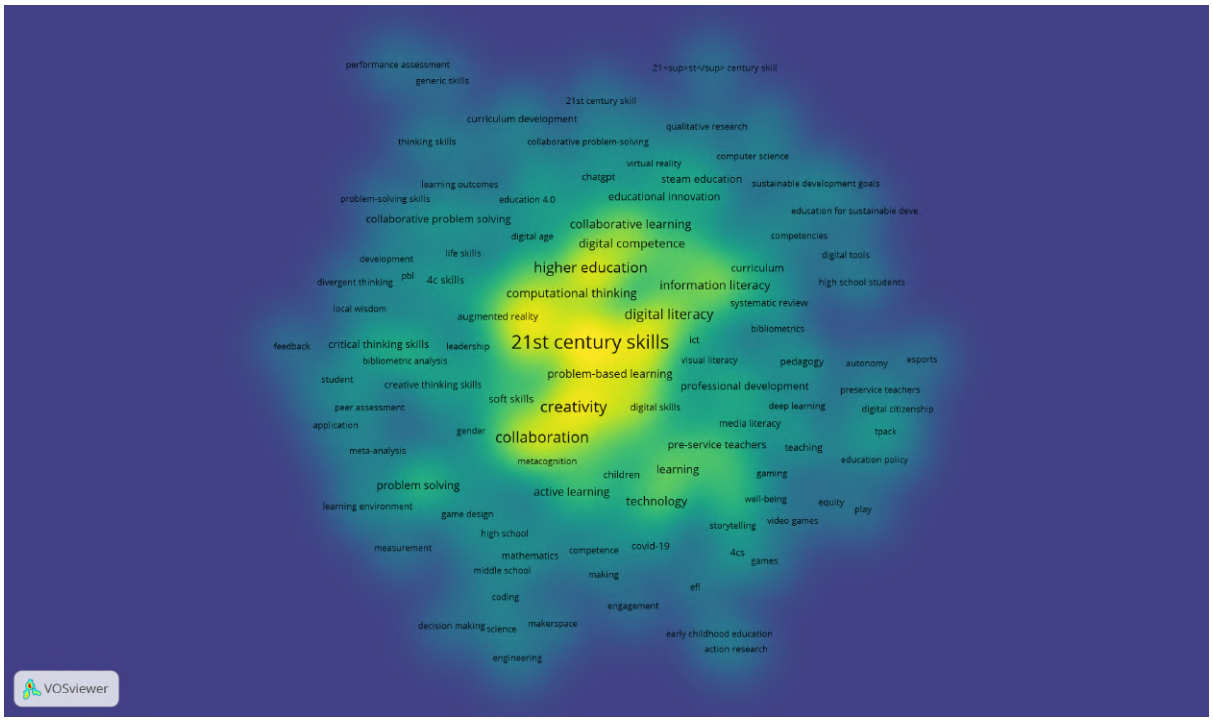


Figure 4. Keyword density visualization

The greatest density shown in Figure 4 was centered on "21st century skills," with closely surrounding areas involving creativity, collaboration, digital literacy, higher education, learning, critical thinking, and computational thinking. Digital literacy occupied the same concentrated central region as several established competency constructs. This pattern reinforces the network evidence that digitally oriented and 4C-related competencies

were embedded within a shared conceptual structure rather than occupying independent or weakly connected bibliometric regions.

Lower-density regions included more specialized topics such as digital citizenship, gaming, coding, assessment, makerspaces, and early childhood education. These themes remained connected to the wider network but showed lower concentration than the central 21st-century-skills region. Taken together, Figures 2, 3, and 4 provide complementary evidence regarding conceptual proximity, relative temporal positioning, and thematic concentration, with a consistent pattern of structural connection among the 4Cs, digital literacy, computational thinking, information literacy, and technology-supported educational research.

International Collaboration Structure

Figure 5 presents the country co-authorship network and complements the publication, citation, and collaboration indicators reported for countries in Table 2. The map provides a visual representation of how national research communities were linked through co-authorship relationships and identifies countries occupying prominent positions within the international network. Its interpretation is combined with international collaboration TLS and the overall international co-authorship percentage because visual node size and location alone cannot indicate the proportion of the entire corpus produced through cross-national collaboration.

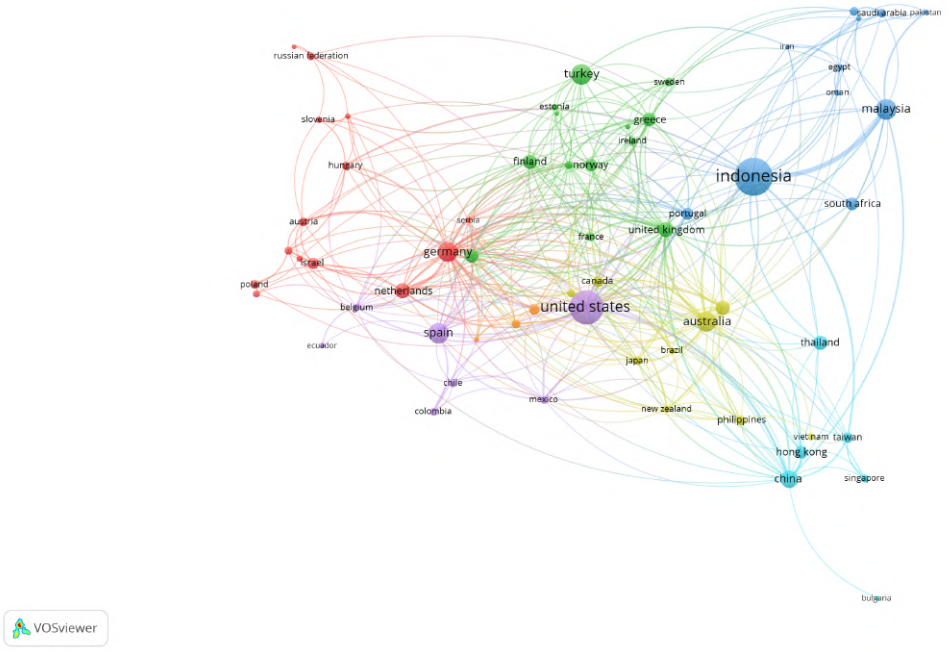


Figure 5. Country co-authorship network

Figure 5 shows prominent nodes for Indonesia, the United States, Germany, China, Malaysia, Australia, Turkey, and the United Kingdom. The United States occupied a central network position, consistent with its international collaboration TLS of 16,225, while Indonesia also appeared as a major node and recorded the highest publication output. The network additionally showed collaboration among Asian countries including Indonesia, Malaysia, China, Thailand, Singapore, and Vietnam, while European countries formed another interconnected portion of the collaboration structure.

The international collaboration network should be considered alongside the overall international co-authorship rate of 15.8%. Although Figure 5 demonstrates visible cross-

national relationships and geographical distribution of research activity, internationally co-authored publications remained a minority of total outputs. The corpus can therefore be described as internationally connected but still substantially dependent on domestic or nationally concentrated publication activity. This distinction is important because national productivity and visibility in the international collaboration network represent related but different dimensions of the field.

Thematic Evolution

Thematic Evolution Across 2015–2025

Figure 6 presents the thematic-evolution map across four analytical periods: 2015–2020, 2021–2022, 2023–2024, and 2025. The visualization traces connections among major themes across successive periods and provides evidence of continuity, differentiation, and changes in thematic terminology. Because the four periods are unequal in duration, the map is interpreted primarily in terms of thematic relationships and changing topic representation rather than as a direct comparison of absolute research volume or thematic intensity across chronologically equivalent intervals.

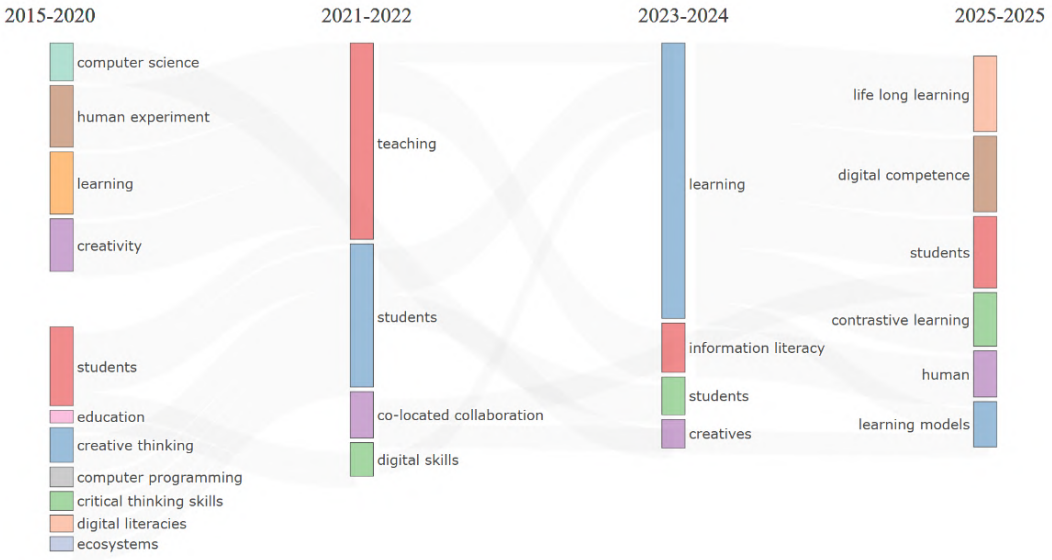


Figure 6. Thematic evolution map

During 2015–2020, prominent themes included computer science, learning, creativity, students, education, creative thinking, computer programming, critical thinking skills, digital literacies, and ecosystems. In 2021–2022, the thematic structure included teaching, students, co-located collaboration, and digital skills. The 2023–2024 period was characterized by learning, information literacy, students, and creativity-related terminology, whereas the 2025 slice included lifelong learning, digital competence, students, learning models, and more specialized technology-oriented concepts.

Across these periods, digital-related terminology became increasingly differentiated, progressing descriptively from digital literacies to digital skills, information and data literacy, and subsequently digital competence and digital transformation. This pattern does not establish that one construct causally evolved into another, but it demonstrates changes in how digital-related themes were represented within successive portions of the literature. At the same time, creativity, learning, critical thinking, teaching, and student-oriented themes remained visible across multiple periods, indicating thematic continuity alongside increasing specialization.

Time Slice 1: 2015–2020

Figure 7 presents the strategic thematic structure of the 2015–2020 period according to centrality and density. This earliest time slice provides the baseline thematic configuration against which subsequent periods can be examined. Particular attention is directed toward teaching, e-learning, critical thinking, creativity, project-based learning, STEM, programming, and digital literacies because these themes represent important cognitive, pedagogical, disciplinary, and technological dimensions that either persist or become further differentiated in the later thematic maps.

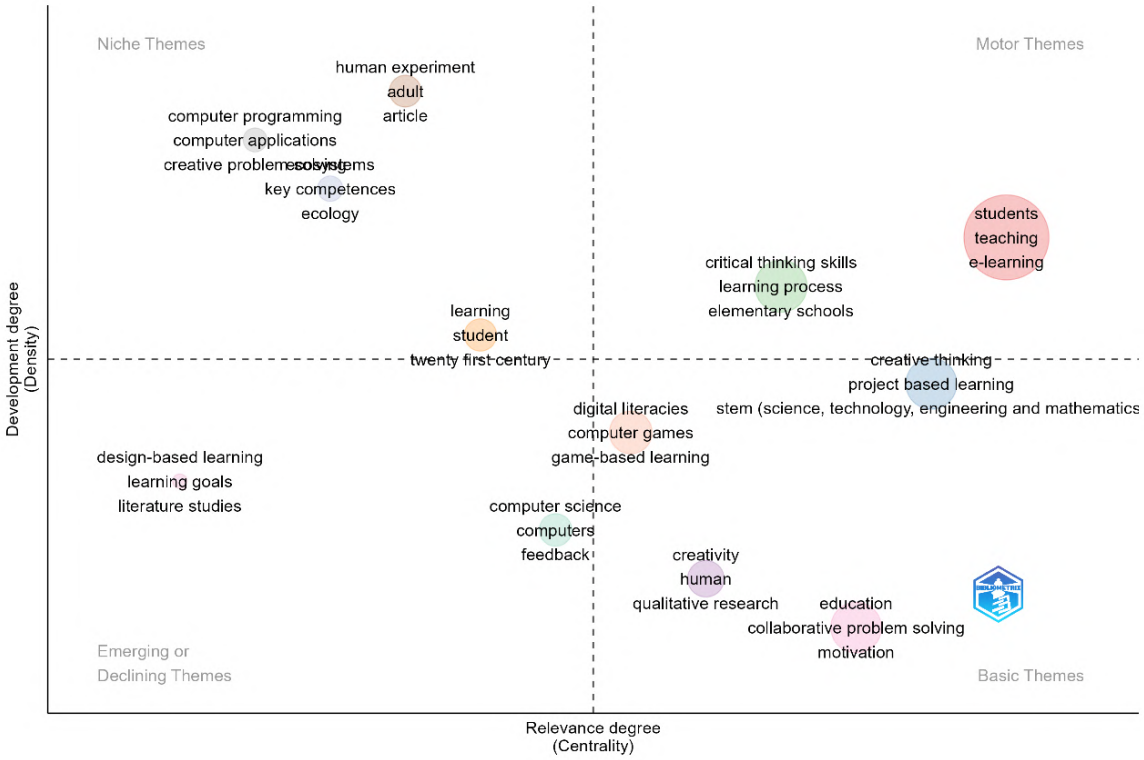


Figure 7. Time Slice 1: 2015–2020

Students, teaching, and e-learning occupied the motor-theme quadrant in Figure 7, indicating comparatively high centrality and thematic development. Critical thinking skills, learning process, and elementary schools were also positioned near the motor-theme region. Computer programming, computer applications, creative problem solving, key competencies, and ecology appeared within the niche-theme quadrant, reflecting themes with relatively strong internal development but weaker connections with the broader thematic structure during this earliest analytical period.

Creative thinking, project-based learning, STEM, creativity, education, collaborative problem solving, and motivation occupied the basic-theme quadrant, indicating broad connectivity with lower internal thematic density. Digital literacies, computer games, game-based learning, design-based learning, learning goals, and literature studies appeared closer to the emerging/declining region. Digital-literacy-related research was therefore visible during 2015–2020 but remained less structurally consolidated than several teaching, learning, critical-thinking, creativity, and project-oriented themes represented elsewhere in the strategic map.

Time Slice 2: 2021–2022

Figure 8 presents the strategic thematic configuration for 2021–2022 and enables comparison with the broader structure identified during 2015–2020. The map contains a more

concentrated set of themes involving teaching, critical thinking, learning, digital skills, e-learning, engineering education, and collaboration. This time slice is particularly relevant for determining whether digital terminology had developed greater internal coherence while established cognitive and pedagogical competencies continued to occupy central positions within the thematic organization of the field.

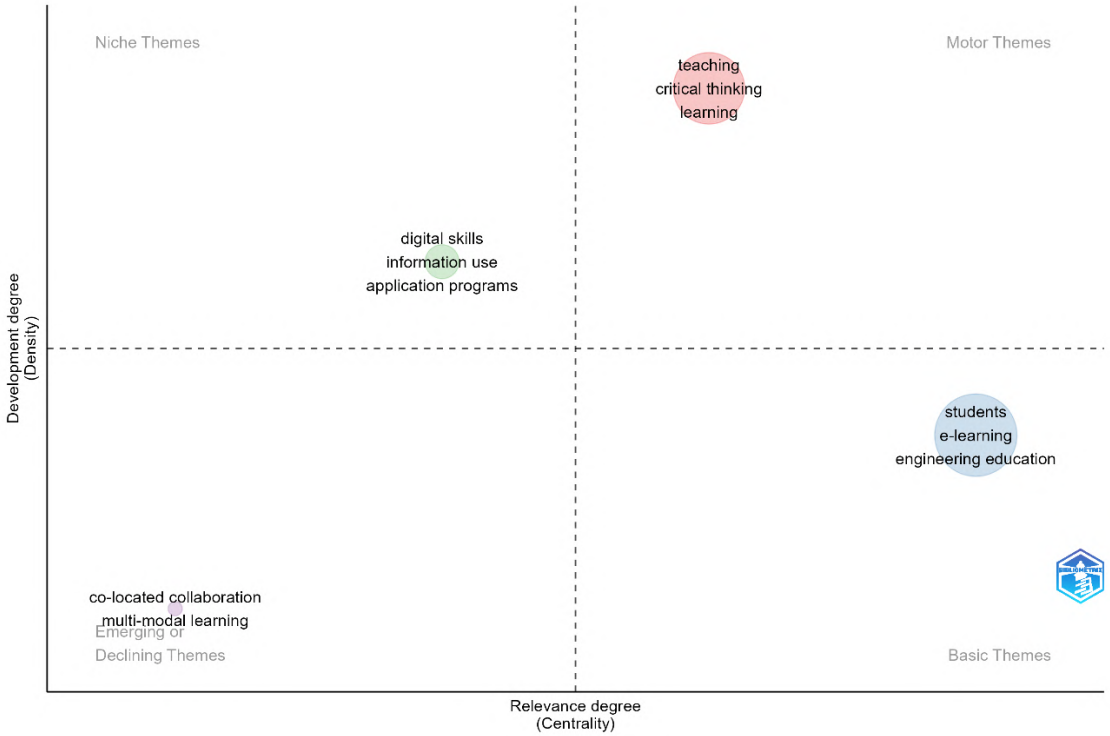


Figure 8. Time Slice 2: 2021–2022

Teaching, critical thinking, and learning formed the principal motor theme in Figure 8, demonstrating comparatively high development and strong connectivity with the broader research structure. Digital skills, information use, and application programs occupied the niche-theme quadrant, indicating a recognizable specialized area with greater internal development but lower centrality than the teaching–critical-thinking–learning grouping. Students, e-learning, and engineering education occupied the basic-theme region, retaining broad connections across the field despite comparatively lower internal density.

Co-located collaboration and multimodal learning appeared closer to the emerging/declining quadrant, reflecting comparatively limited structural consolidation during 2021–2022. Compared with the preceding period, Figure 8 shows that digital skills had become a more clearly identifiable thematic grouping, while teaching, learning, and critical thinking remained strongly positioned. The resulting configuration therefore documents increasing specialization of digitally oriented terminology without indicating that established cognitive and educational themes had been displaced from the thematic structure.

Time Slice 3: 2023–2024

Figure 9 presents the strategic thematic structure for 2023–2024 and shows further differentiation within digitally oriented and innovation-related research. Two groupings are particularly relevant: one involving creativity-related terminology, metaverses, and innovation, and another involving information literacy and data literacy. The map also retains students, teaching, and engineering education within broadly connected positions, allowing increasingly specialized digital and immersive themes to be examined alongside persistent educational contexts and established teaching-related structures.

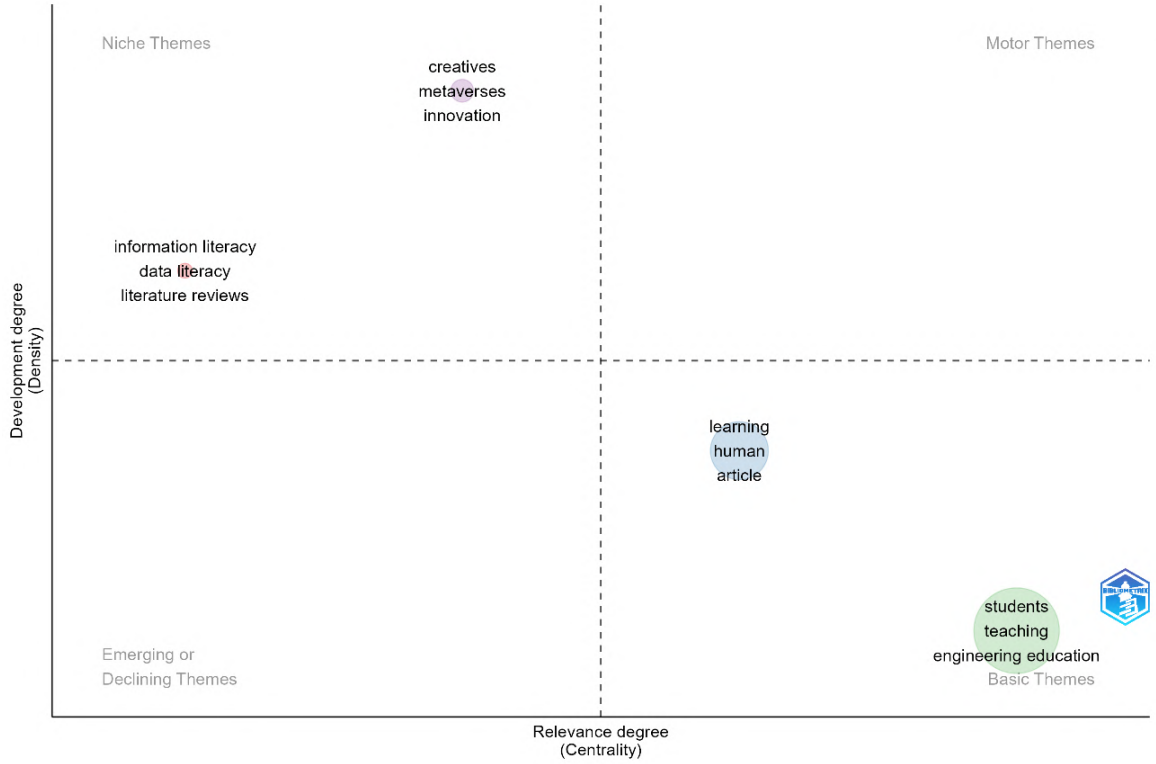


Figure 9. Time Slice 3: 2023–2024

The niche-theme quadrant contained a grouping involving creatives, metaverses, and innovation, together with another grouping containing information literacy, data literacy, and literature reviews. The presence of information literacy and data literacy represents greater thematic specificity than the broader digital-literacy and digital-skills terminology identified in earlier periods. Students, teaching, and engineering education occupied the basic-theme area, maintaining broad structural connections within the field while more specialized digital and innovation-related topics became increasingly visible.

The map also contained generic indexed terms such as human and article. These labels were retained as part of the generated bibliometric structure but provide limited conceptual specificity for interpreting competency-related themes. Greater analytical emphasis is therefore placed on information literacy, data literacy, metaverse-related research, creativity, innovation, teaching, and student learning. The 2023–2024 period consequently shows increasing specialization within the digital and immersive portions of the literature while continuing to retain established educational settings as connecting thematic contexts.

Time Slice 4: 2025

Figure 10 presents the strategic thematic structure for 2025 and provides the most recent representation of topic organization within the corpus. The map is particularly useful for examining whether digital competence, digital transformation, robotics, robot programming, and machine-learning-related terminology had developed into identifiable thematic groupings by the end of the study period. The figure also allows these specialized topics to be viewed alongside continuing educational themes such as teaching, students, learning, creativity, engineering education, and broader competency-related concepts.

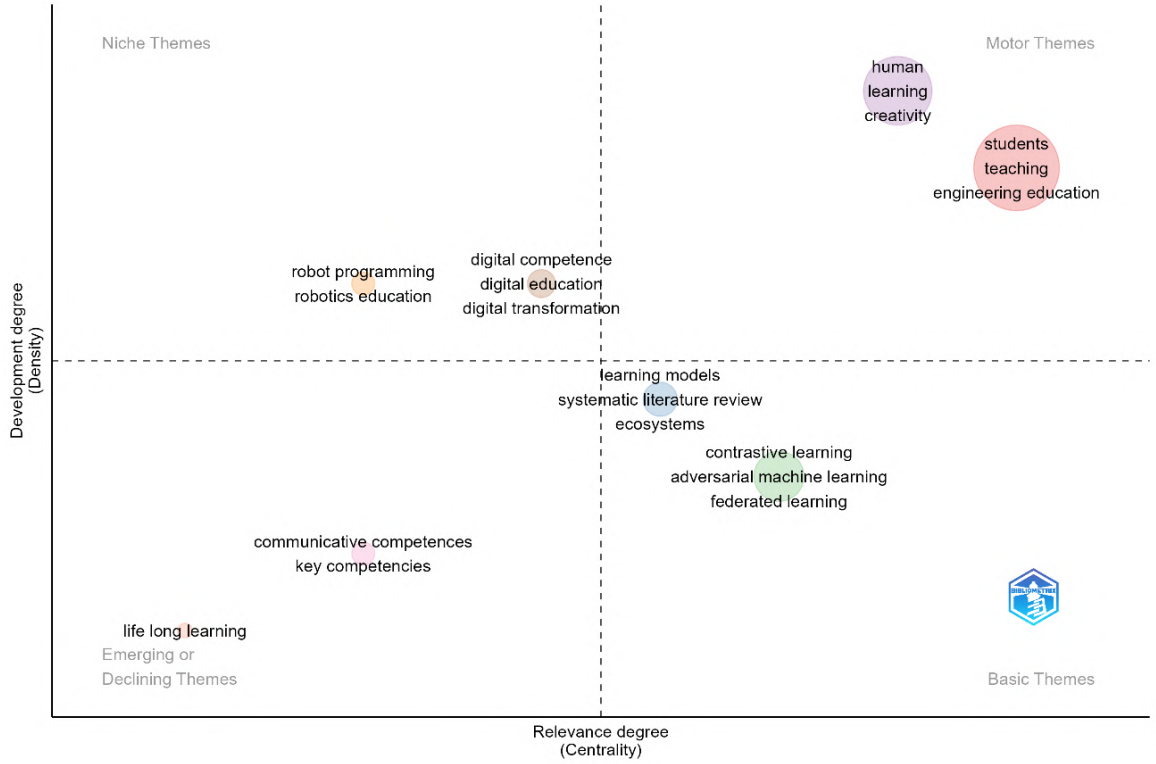


Figure 10. Time Slice 4: 2025

Robot programming and robotics education occupied the niche-theme quadrant, indicating a comparatively developed but specialized computational and technological area. Digital competence, digital education, and digital transformation formed another developed grouping positioned above the central density line. Students, teaching, engineering education, creativity, and learning remained prominent within the wider structure, while learning models, systematic literature review, and ecosystems occupied intermediate positions. The map therefore shows coexistence between established educational themes and increasingly differentiated digital and computational terminology.

Contrastive learning, adversarial machine learning, and federated learning appeared within the basic-theme area, showing that advanced machine-learning terminology had entered the corpus without yet demonstrating high thematic density. Communicative competences, key competencies, and lifelong learning occupied the emerging/declining quadrant. Because this quadrant can represent either developing or weakening themes, their position alone does not justify classifying them as established emerging fronts. Across Figures 7–10, the more consistent pattern is increasing differentiation toward digital skills, information and data literacy, digital competence, digital transformation, robotics, and machine-learning-related concepts.

Integrated Thematic Structure

The combined performance and science-mapping results were synthesized into five higher-order thematic domains: core 4C and 21st-century competencies; digital and information competencies; pedagogical and technology-supported learning; assessment and learning outcomes; and computational, collaborative, and STEM/STEAM integration. These domains do not represent five fixed software-generated clusters. Instead, they summarize recurring patterns across keyword proximity, term prominence, overlay and density visualizations, thematic evolution, strategic diagrams, highly cited publications, source profiles, institutional and national profiles, and representative bibliographic records.

Core 4C and 21st-Century Competencies

The first thematic domain comprises critical thinking, creativity, communication, collaboration, problem solving, soft skills, and broader 21st-century competencies. The keyword co-occurrence network positioned "21st century skills" at the center of the conceptual structure, with creativity and collaboration among the most prominent adjacent terms. Critical-thinking-related terminology appeared repeatedly across the keyword maps, highly cited publications, publication-source profiles, country profiles, and strategic thematic analyses, demonstrating continued structural visibility of the core competencies throughout the period examined.

The highly cited literature and source profiles provide additional evidence for this domain. Thornhill-Miller et al. focused explicitly on assessment and institutional promotion of the 4Cs, while Rios et al. identified communication, collaboration, problem solving, and critical thinking among prominent workplace competencies. Thinking Skills and Creativity also showed substantial concentration on creativity, critical thinking, metacognition, design thinking, problem solving, communication, collaboration, and competency assessment. Across these outputs, the 4C-related constructs remained among the most recurrent and structurally visible competencies in the corpus.

Digital and Information Competencies

The second thematic domain comprises digital literacy, digital competence, information literacy, media literacy, technology literacy, ICT literacy, computational thinking, data literacy, AI literacy, digital creativity, and related digitally mediated competencies. Digital literacy occupied a prominent central position in both the keyword network and density visualization, while computational thinking and information literacy were positioned close to broader 21st-century-skills terminology. These patterns indicate that digital and information competencies were structurally embedded within the larger competency field rather than appearing solely as isolated technology-related topics.

The temporal analyses provide additional differentiation within this domain. Digital literacies appeared among relatively weakly consolidated themes during 2015–2020, digital skills formed a developed niche theme during 2021–2022, information literacy and data literacy became identifiable specialized themes during 2023–2024, and digital competence, digital education, and digital transformation formed a comparatively developed grouping in 2025. The results therefore document increasing specificity in digitally oriented terminology and thematic organization across the study period.

Pedagogical and Technology-Supported Learning

The third thematic domain concerns the instructional environments and learning strategies associated with essential competencies. The keyword network included active learning, problem-based learning, project-based learning, collaborative learning, flipped classroom, STEM education, educational innovation, game design, professional development, and technology-supported learning. These terms occurred close to major competency-related nodes, showing that the literature frequently examined competency development in relation to specific pedagogical arrangements, disciplinary contexts, collaborative activity, and technology-supported learning environments rather than as context-independent educational outcomes.

Publication-source and temporal patterns reinforced this domain. Journal of Physics: Conference Series and AIP Conference Proceedings were strongly associated with STEM/STEAM, project-based learning, problem-based learning, inquiry, and digital learning, whereas other sources broadened the instructional landscape toward serious games,

gamification, immersive technologies, peer assessment, teacher education, EFL, and TVET. Across Figures 7–10, teaching, learning, e-learning, students, engineering education, and learning models remained recurrent thematic elements, demonstrating sustained interaction between competency research and educational design.

Assessment and Learning Outcomes

The fourth thematic domain includes competency assessment, performance measurement, learning outcomes, collaborative problem-solving assessment, computational-thinking assessment, critical-thinking assessment, creativity assessment, and digital-competence measurement. Assessment-related terminology was connected with major competency concepts within the keyword network rather than forming an entirely separate research area. Its recurrence across source profiles, country profiles, highly cited documents, and thematic groupings demonstrates that measurement represents a cross-cutting component of research involving cognitive, interpersonal, computational, digital, and broader 21st-century competencies.

The contributor profiles further illustrate this cross-cutting assessment orientation. Thinking Skills and Creativity contained substantial attention to creativity and critical-thinking assessment, Education Sciences included computational-thinking and digital-competence measurement, and Frontiers in Education incorporated critical online reasoning and competency assessment. Country profiles also showed work involving performance assessment, collaboration assessment, formative assessment, multimodal analytics, and game-based assessment in Germany, China, the Netherlands, and the United States. The results therefore position assessment as a recurring component distributed across multiple competency areas and educational settings.

Computational, Collaborative, and STEM/STEAM Integration

The fifth thematic domain connects collaborative problem solving, computational thinking, programming, STEM/STEAM education, interdisciplinary learning, critical thinking, creativity, communication, and problem solving. Computational thinking occupied a prominent position near digital literacy and higher education in the keyword network, while collaborative problem solving, STEM education, problem solving, and critical-thinking-related terms were connected through the broader conceptual structure. This pattern shows that computational and collaborative competencies were frequently investigated together with disciplinary, interdisciplinary, and technology-supported educational environments.

Highly cited documents and source profiles provide additional evidence for this intersection. Nouri et al. linked programming with computational thinking, digital competence, collaboration, language skills, and creative problem solving, while Stehle and Peters-Burton connected STEM-school environments with collaboration, communication, real-world problem solving, and technology-supported learning. Temporal evidence also shows increasing specificity, with computer science and computer programming appearing during the earliest period and robot programming and robotics education occupying a developed specialized position in the 2025 strategic map.

Emerging and Specialized Research Themes

Several additional topics appeared across the performance and science-mapping outputs without showing the same degree of structural prominence as the five higher-order domains. These included artificial intelligence, ChatGPT, robotics, digital transformation, design thinking, metacognition, digital citizenship, sustainability competence, lifelong learning, immersive learning, game-based learning, socio-emotional competence, and

Education 5.0. Because these topics differed substantially in centrality, density, citation visibility, and temporal consolidation, they are more appropriately treated as emerging or specialized research areas rather than as one homogeneous thematic category.

AI-related topics were visible through highly cited studies on teacher AI digital competence and ChatGPT, while the later thematic structures introduced robot programming, robotics education, digital transformation, contrastive learning, adversarial machine learning, and federated learning. The 2023–2024 map also identified metaverses, innovation, information literacy, and data literacy as specialized themes, whereas digital competence, digital education, digital transformation, robot programming, and robotics education occupied more clearly developed thematic positions in 2025. These patterns demonstrate increasing technological specialization without implying equal levels of thematic maturity across all recently visible topics.

Sustainability competence, digital citizenship, socio-emotional competence, leadership, design thinking, immersive learning, and employability-related capabilities appeared mainly as specialized or cross-cutting strands across source and country profiles. Communicative competences, key competencies, and lifelong learning occupied the emerging/declining quadrant in the 2025 strategic map and therefore cannot be classified confidently as emerging on the basis of quadrant position alone. Across the Results as a whole, the strongest recurring pattern is the continued structural presence of 4C-related competencies alongside increasing differentiation of digital, informational, computational, assessment-related, and technology-supported competency domains.

Discussion

The bibliometric patterns indicate that research on essential competencies has developed through expansion and increasing conceptual differentiation rather than through the replacement of established competency frameworks. Critical thinking, creativity, communication, and collaboration remain highly visible across the conceptual structure, highly cited literature, publication-source profiles, and temporal patterns, while digital literacy, digital competence, computational thinking, information literacy, data literacy, AI-related competence, assessment, and technology-supported learning have become increasingly interconnected with them. The resulting structure is therefore not characterized by a simple transition from established 21st-century skills toward digital competencies. Instead, it reflects a progressively differentiated knowledge domain in which cognitive, interpersonal, informational, computational, technological, and contextual capabilities increasingly coexist.

Growth, Dispersion, and Multidimensional Scholarly Prominence

The substantial growth of the corpus and its distribution across a large number of publication sources indicate that essential-competency research has developed as a broad interdisciplinary area rather than within a single educational specialty. Previous bibliometric studies have already documented substantial activity in particular subdomains, including scientific creativity, project-based learning and 21st-century skills, and scientific literacy, but these streams represent only parts of a wider competency landscape (Chamidah et al., 2024; Prahani et al., 2024; Yuliana et al., 2025). The present structure shows that research on essential competencies extends simultaneously across STEM and STEAM education, educational technology, teacher education, language learning, vocational education, assessment, sustainability, computing, and emerging digital environments.

This breadth is also visible in the diversity of educational and professional settings represented by individual studies. Research has examined the integration of 4C skills in

English-for-nursing textbooks, 21st-century skills in school science textbooks, general competencies among environmental-science graduates, and employer expectations for accounting graduates under disruptive technological conditions (Handayani et al., 2025; Almomani & Alnasraween, 2024; Puriboriboon, 2025; Vera Galván et al., 2024). Such diversity demonstrates that essential competencies are no longer associated exclusively with general school education. They are increasingly embedded in disciplinary curricula, professional preparation, employability, and sector-specific learning environments.

The contributor patterns further demonstrate that scholarly prominence is multidimensional. High publication productivity does not necessarily correspond to high citation visibility or strong bibliometric connectivity. Conference-oriented sources contributed substantial publication volume, whereas specialist outlets such as Thinking Skills and Creativity accumulated considerably greater citation visibility and bibliographic-coupling strength despite producing fewer documents. Comparable asymmetries were evident among authors, institutions, and countries. These differences reinforce the importance of distinguishing productivity, accumulated citation attention, and relational connectivity because each reflects a different form of participation in the scholarly structure rather than a single hierarchy of importance.

The coexistence of high-volume national research communities and more highly cited international contributions also reflects the heterogeneous development of the field. Large bodies of competency-oriented research are being produced through context-specific educational experimentation, while other publications circulate more widely across disciplinary and national boundaries. This pattern is consistent with the conceptual breadth of 21st-century competency research itself, which increasingly incorporates not only cognitive and interpersonal skills but also self-regulation, social-emotional dimensions, ethical considerations, employability, and technology-mediated capabilities (Feraco et al., 2025; Shek et al., 2025). Scholarly dispersion therefore appears to reflect both thematic expansion and the growing number of educational settings in which competency frameworks are being interpreted and applied.

The 4Cs as a Persistent Conceptual Core Within a Broader Competency Structure

One of the clearest findings is the continued structural visibility of critical thinking, creativity, communication, and collaboration. The central position of 21st-century skills and the strong presence of creativity, collaboration, and critical-thinking-related terminology indicate that the 4Cs continue to organize a substantial portion of the literature. Their persistence is consistent with evidence linking these competencies to both educational and professional contexts. The 4Cs continue to be discussed in relation to future education and work, while communication, collaboration, problem solving, and critical thinking remain visible in analyses of workplace requirements (Rios et al., 2020; Thornhill-Miller et al., 2023).

Their durability is also evident across substantially different educational settings. Critical thinking and cooperativity have been examined as interrelated dimensions of 21st-century skills in higher education, while 4C integration has been investigated in nursing-oriented English materials, science curricula, and mathematics-teacher activities (Handayani et al., 2025; Koçak et al., 2021; Almomani & Alnasraween, 2024; Zakaria et al., 2025). These studies differ in discipline, learner population, and educational purpose, yet they continue to use overlapping constructs of critical thinking, creativity, communication, and collaboration. The recurrence of these constructs across different settings helps explain their sustained centrality within the broader bibliometric structure.

The persistence of the 4Cs does not, however, imply that they provide a complete taxonomy of contemporary competence. Digital literacy, digital competence, computational thinking, information literacy, media literacy, data literacy, and AI-related capabilities increasingly occupy the same conceptual space. Digital skills have long been shown to overlap with communication, collaboration, creativity, critical thinking, problem solving, and information management (van Laar et al., 2017), while comparative digital-competence frameworks incorporate information handling, communication, collaboration, digital-content creation, teaching and learning, and ethical dimensions (Mattar et al., 2022). More recent competency formulations further extend the field toward technology use, connectivity, computational thinking, self-direction, global competence, and cross-cultural capability (Schmitz et al., 2024; Wardani et al., 2025).

This expansion is compatible with broader interpretations of 21st-century competence that extend beyond a narrow set of cognitive skills. The OECD Learning Compass-oriented analysis by Shek et al. (2025), for example, situates 21st-century development within a wider competency architecture, while work integrating self-regulated learning with social, emotional, and behavioral skills illustrates how contemporary soft-skill frameworks increasingly intersect with personal and interpersonal regulation (Feraco et al., 2025). The bibliometric expansion observed here therefore reflects not only technological change but also a widening understanding of the competencies required for learning, participation, adaptability, and professional activity.

The 4Cs are consequently better interpreted as persistent foundational capabilities rather than as an exhaustive list of contemporary competencies. Critical thinking remains relevant when learners evaluate digital or AI-generated information; creativity remains relevant when learners generate technologically mediated products or solutions; communication increasingly occurs through multimodal and platform-based environments; and collaboration increasingly involves distributed, technology-supported, and sometimes human-machine activity. Their persistence is therefore associated with their applicability across changing contexts rather than with isolation from technological development.

Conceptual integration should nevertheless not be confused with conceptual equivalence. Computational thinking introduces decomposition, abstraction, algorithmic reasoning, and automation into problem-solving processes, whereas information literacy emphasizes locating, evaluating, interpreting, and responsibly using information. Digital competence includes technological, informational, communicative, creative, and ethical dimensions, whereas critical thinking remains a broader reasoning capability applicable to both digital and non-digital contexts. The increasing proximity among these constructs therefore indicates relational integration without eliminating their theoretical distinctiveness.

Digital Competence as a Connective Layer in Contemporary Learning

The temporal structure provides an important perspective on the changing role of digital competence. Digital literacies were already visible during 2015–2020, digital skills appeared as a more developed specialized theme during 2021–2022, information and data literacy became more distinct during 2023–2024, and digital competence, digital education, and digital transformation occupied more developed thematic positions in 2025. This pattern is better understood as increasing thematic differentiation than as a linear sequence in which one construct replaces another. The vocabulary of the field has become more specialized as digitally mediated educational activities have become more complex.

This differentiation is consistent with conceptual work positioning digital skills within a wider configuration of 21st-century competencies rather than as an isolated technical

domain (van Laar et al., 2017). Comparative analyses of digital-competence frameworks similarly show that digital competence incorporates informational, communicative, collaborative, creative, pedagogical, and ethical elements (Mattar et al., 2022). Teacher education adds another dimension because digital competence becomes relevant not only to tool use but also to pedagogical decision making and the development of learners' broader competencies (Napal-Fraile et al., 2018). Technology-supported language learning likewise demonstrates how digital environments can intersect with communication and other 21st-century capabilities rather than functioning as a separate skills domain (Shadiev & Wang, 2022).

Computational thinking provides a particularly clear illustration of this integration. Programming-related research associates computational activity with digital competence, collaboration, cognitive capabilities, and creative problem solving (Nouri et al., 2020), while active-learning environments have also been used to examine the joint development of computational thinking and broader 21st-century competencies (Buitrago-Flórez et al., 2021). Meta-analytic work on programming in K–12 education further positions programming within multidimensional skill development rather than solely within technical computing outcomes (Hu, 2024). Computational thinking has also been explicitly connected to teacher education, highlighting its relevance to pedagogical preparation as well as student learning (Yadav et al., 2017).

Information literacy represents another increasingly differentiated component of the digital competency structure. It now extends beyond locating information toward credibility evaluation, interpretation, security awareness, and responsible information use (Banek-Zorica et al., 2025). These functions overlap substantially with critical thinking, but their application to digital information environments gives information literacy a distinct focus. Similar multidimensionality is evident in attempts to measure digital competence in professional contexts, where digital capability cannot be reduced to basic technology operation alone (Mainz et al., 2024). The increasing visibility of information and data literacy therefore reflects a shift from concerns about technological access toward more complex concerns about judgment, interpretation, and responsible participation.

Artificial intelligence intensifies these relationships because AI-supported environments combine technical, cognitive, communicative, and ethical demands. Teacher AI digital competence has been associated with digital teaching, AI-enhanced learning, and assessment (Ng et al., 2023), while generative AI has been examined in relation to language learning, human-machine collaboration, and responsible educational use (Kostka & Toncelli, 2023). More recent studies extend these relationships to AI-assisted STEAM lesson planning, algorithmic thinking, and chatbot-supported teacher education (Luo & Tahir, 2025; Zábrádi et al., 2025). AI-supported debate in language-learning contexts further illustrates how emerging technologies can intersect with communication, argumentation, and disciplinary competence rather than functioning only as technical tools (Butarbutar et al., 2025).

The widening digital environment is also visible through immersive and extended-reality applications. Research on virtual and augmented reality has linked such environments with broader 21st-century skills (Papanastasiou et al., 2019), while immersive augmented-reality mobile learning has been investigated in relation to Industry 4.0 skill development in vocational education (Efendi et al., 2025). Metaverse-based higher education has similarly been examined in relation to employability perceptions (de Matías-Batalla & Nicolás-Sans, 2025). These strands reinforce the interpretation that digital competence increasingly operates as a connective layer across learning, professional preparation, communication, problem solving, and technology-mediated participation.

The visibility of robotics, robot programming, digital transformation, and machine-learning-related concepts in the later thematic structure extends this pattern further. Their appearance shows that the computational boundary of competency research is widening, but it does not indicate that advanced technical expertise has become a universal competency requirement. Rather, such domains create specialized environments in which computational reasoning, disciplinary knowledge, problem solving, creativity, collaboration, and information judgment can intersect. The expansion therefore represents diversification of the ecosystem rather than the formation of a universal technology-centered hierarchy.

Pedagogy as the Context for Competency Enactment

The close relationship between competency terms and pedagogical concepts indicates that essential competencies are increasingly studied through the learning environments in which they are practiced. Project-based learning, problem-based learning, inquiry, collaborative learning, active learning, STEM/STEAM, flipped learning, game-based learning, design-oriented approaches, makerspaces, challenge-based learning, and technology-supported environments recur across the literature. Their significance lies in creating situations in which learners must mobilize several competencies simultaneously rather than treating critical thinking, creativity, communication, collaboration, and digital competence as isolated educational outcomes.

Project-based and inquiry-oriented approaches illustrate this relationship clearly. Project-based learning has been associated with critical thinking, problem solving, collaboration, and engagement in mathematics education (Rehman et al., 2024), while inquiry-based learning has similarly been connected with critical thinking, collaboration, knowledge construction, learner agency, and digital-tool use (Chu et al., 2017). Integrated STEM project-based learning has also been examined in vocational education in relation to competence and employability (Akmal et al., 2025), and STEM-oriented environments connect disciplinary knowledge with communication, collaboration, creativity, and real-world problem solving (Amri et al., 2024; Papadopoulou et al., 2025; Stehle & Peters-Burton, 2019).

The relevance of project-oriented learning is not restricted to a single sector or instructional format. Project-based interventions have been examined in rural post-pandemic educational contexts, while problem-based flipped learning extends related principles into vocational learning environments (Arrieta-Cohen et al., 2024; Mustaqim et al., 2025). Research on teachers' understanding and application of project-based learning together with 4C skills additionally shows that the relationship between pedagogy and competency development includes an implementation dimension at the teacher level (Priyohutomo et al., 2025). These strands reinforce the idea that pedagogical labels alone do not constitute competency development; the way a model is interpreted and enacted remains central to the competencies that become available for practice.

A similarly diverse pattern appears in creative and collaborative learning environments. Digitizing written stories into film through project-based activity situates communication, creative production, collaboration, and digital practice within the same learning process (Ampo et al., 2025). Design-thinking work in the fine arts places creative activity within another form of structured problem solving (King & McCall, 2024), while hackathon-based learning provides an intensive environment for combining problem solving, collaboration, and other 21st-century capabilities (Gal, 2025). Collaborative classroom activities have also been explicitly designed around soft-skill development, and cooperative learning has been examined in relation to pre-service teachers' understanding of 21st-century skills (Brieven et al., 2025; Salvador-Garcia & Ribés, 2025).

Online and technology-rich pedagogies further diversify these contexts. Challenge-based learning has been examined in online settings, demonstrating the movement of authentic and collaborative tasks beyond conventional face-to-face instruction (Zaccaria et al., 2025). Makerspace research similarly emphasizes prototyping, co-design, and opportunities to practice complex competencies, while augmented-reality research has explored how makerspace experiences can be designed through iterative prototyping and co-design processes (Ioannou et al., 2025; Radu et al., 2023). These environments illustrate how physical and digital resources can become part of a broader instructional ecology rather than functioning as independent technological interventions.

The simultaneous presence of several competencies within one learning environment does not imply equivalent development across competencies. STEM-based interventions can produce different patterns for communication and collaboration, while digital-game interventions also show different effects across the four Cs (Amri et al., 2024; Cheng & Weatherly, 2025). This variation is theoretically important because it demonstrates that competencies remain empirically distinguishable even when activated within the same pedagogy. Different competencies may depend on different forms of interaction, task demands, feedback, learner autonomy, reflection, or disciplinary integration.

Technology itself therefore cannot be treated as the mechanism of competency development. What appears consistently across project-based, inquiry-oriented, makerspace, immersive, collaborative, and challenge-based settings is the organization of meaningful activity around problems, design, communication, coordination, production, and reflection. Technology can expand these opportunities through simulation, multimodal representation, information access, or collaborative production, but the competencies that become visible depend on what learners are required to do with those resources.

Assessment and Operationalization as a Methodological Tension

The increasing complexity of the competency landscape is accompanied by substantial challenges in assessment. Assessment-related concepts recur across critical thinking, creativity, collaborative problem solving, computational thinking, digital competence, and learning outcomes, indicating that measurement has become a cross-cutting concern. The resulting tension lies between the broad endorsement of essential competencies and the more difficult task of operationalizing them through evidence that adequately represents complex, multidimensional, and context-sensitive performance.

The 4Cs themselves illustrate this problem. Assessment and certification remain major issues in the institutionalization of creativity, critical thinking, communication, and collaboration (Thornhill-Miller et al., 2023), while multidimensional scales continue to be developed for learning and innovation skills (Kayhan & Korkmaz, 2024). Critical-thinking assessment has also been approached through performance-based conceptualization and task design rather than only through conventional knowledge testing (Braun et al., 2020). At a more discipline-specific level, instruments combining science-process skills and critical-thinking skills in physics demonstrate how competency measurement can become embedded within subject-matter learning rather than being detached from disciplinary content (Puspa et al., 2024).

Collaborative problem solving introduces additional complexity because the construct involves both individual reasoning and interpersonal coordination. Systematic work on computer-based collaborative problem-solving assessment shows that digital environments increasingly provide new ways to capture these interactions (Chai et al., 2024). Computational thinking presents a related measurement problem because its operationalization varies across

age groups, tasks, and instruments, as demonstrated by reviews of computational-thinking measures in the early years of schooling (Ocampo et al., 2024). Digital competence likewise remains multidimensional and context dependent, with measurement frameworks differing according to professional and educational settings (Mainz et al., 2024).

The distinction between opportunities to practice a competency and evidence that the competency has developed is especially important. Makerspaces can create extensive opportunities for creativity, communication, collaboration, and problem solving even when those competencies are not explicitly measured (Ioannou et al., 2025). Teacher perspectives and learner backgrounds can also shape how thinking skills are assessed and instructed, indicating that operationalization is influenced by implementation conditions as well as by instrument design (Kamei, 2025). A learning environment may therefore be strongly competency-oriented in principle while providing limited evidence regarding the extent, quality, or durability of actual competency development.

Digital technologies add another methodological layer because they make increasingly detailed process data observable. Temporally sensitive natural-language-processing approaches to team interaction illustrate how communication and collaboration can be examined dynamically rather than only through final products or retrospective questionnaires (Park et al., 2025). Such data can reveal sequences of interaction, responsiveness, participation, or collaborative activity that conventional assessments may overlook. At the same time, digitally traceable behavior remains an indicator of activity rather than direct evidence of the full underlying competence. The growing availability of process data therefore expands assessment possibilities while simultaneously intensifying questions about construct representation, interpretation, fairness, privacy, and comparability.

Assessment consequently represents one of the points at which the expansion of the competency ecosystem becomes most methodologically visible. The increasing number of constructs does not simply create a need for more instruments; it reveals differences in what counts as competent performance across reasoning, collaboration, creativity, information use, computation, and digital participation. The field is therefore characterized by increasing conceptual integration alongside persistent measurement heterogeneity.

Geographic Variation, Collaboration, and Unequal Conditions for Competency Development

The geographical patterns indicate a field that is internationally distributed but unevenly connected. Strong publication activity from several national research communities demonstrates broad engagement with competency-oriented education, while differences in citation visibility and international collaboration reflect distinct forms of scholarly participation. The comparatively modest proportion of internationally co-authored publications further indicates that much of the knowledge base remains embedded within national and institutional research systems. Common competency labels are therefore being examined under substantially different curricular, linguistic, technological, socioeconomic, and institutional conditions.

Context-specific studies illustrate the extent of this variation. The integration of the 4Cs has been examined in Vietnamese Business English education, while 21st-century competencies have been considered in relation to ethical, cultural, and legal dimensions in Central Asian higher education (Ha, 2025; Jalilov et al., 2025). Thai primary-school reform has combined STEM curriculum development with leadership and competency-based priorities, while rural Colombian research has examined project-based learning within a distinct post-pandemic educational environment (Arrieta-Cohen et al., 2024; Supakwong, 2025). Science-curriculum research in Jordan provides another example of how broadly shared competency

terminology becomes embedded in nationally specific curricular structures (Almomani & Alnasraween, 2024).

Variation is also visible across professional and sectoral contexts. Competency research extends from environmental-science graduates to accounting employability, nursing-oriented language materials, vocational education, and hybrid teacher preparation (Handayani et al., 2025; Puriboriboon, 2025; Salleh et al., 2025; Vera Galván et al., 2024). These settings involve different relationships among disciplinary knowledge, communication, technology, professional identity, and workplace expectations. The apparent coherence of broad competency labels therefore coexists with substantial variation in what those competencies mean operationally within different educational and occupational domains.

Digital competence makes contextual inequality particularly visible. Infrastructure, institutional support, lecturer preparedness, and ICT policy can constrain digital-literacy development in higher education, particularly where access to technological resources is uneven (Ndibalema, 2025). Multiliteracy-oriented work similarly draws attention to the combined importance of digital, visual, and information capabilities together with teacher preparation and implementation conditions (Iswatiningsih et al., 2025). Socioeconomic differences can also be associated with digital skills and experiences of online collaborative problem solving, demonstrating that participation in digitally mediated competency development does not occur under equivalent conditions (Luengo-Aravena et al., 2024).

Teacher capability forms another part of this contextual structure. Research on technological pedagogical content knowledge in hybrid learning environments illustrates how digital competence intersects with teachers' capacity to combine technology, pedagogy, and disciplinary content rather than merely operate digital tools (Salleh et al., 2025). Similar issues are reflected in studies examining teachers' understanding and application of project-based learning and 4C skills (Priyohutomo et al., 2025). Competency development is therefore influenced not only by learner characteristics and technological access but also by how educational institutions and educators translate competency frameworks into actual learning environments.

The geographical and contextual evidence consequently complicates any assumption that a single competency framework has identical meaning across educational systems. Differences in curriculum, infrastructure, professional expectations, teacher preparation, language, and institutional capacity shape the forms through which competencies are enacted and observed. The increasing international visibility of digital competence therefore exists alongside substantial differences in the opportunities available for its development.

Integrative Interpretation of the Competency Ecosystem

The combined evidence supports an interpretation of contemporary competency research as an interconnected but differentiated ecosystem rather than as a succession of competing frameworks. Critical thinking, creativity, communication, and collaboration remain broadly distributed across disciplinary, pedagogical, technological, and professional contexts, while digital literacy, information literacy, computational thinking, digital competence, data literacy, and AI-related capabilities introduce increasingly specialized dimensions. The central conceptual distinction is that stronger bibliometric proximity reflects increasing co-occurrence and relational integration, but it does not establish theoretical equivalence among the competencies.

The broader literature reinforces this relational interpretation. Digital creativity illustrates the intersection of creative processes with technology-mediated environments (Cojocariu & Boghian, 2024), while technology-supported language learning demonstrates the

simultaneous relevance of disciplinary learning, digital environments, and broader 21st-century skills (Shadiev & Wang, 2022). Computational-thinking research similarly connects algorithmic and problem-solving processes with active learning and broader competency development rather than isolating computation as a purely technical domain (Buitrago-Flórez et al., 2021; Nouri et al., 2020). These intersections help explain why contemporary competency research increasingly appears connected without becoming conceptually homogeneous.

This distinction between conceptual differentiation and functional integration is especially important for digital competence. Digital competence does not appear simply as another item added to a longer inventory of educational skills. Its relationships with information evaluation, communication, collaboration, creativity, computational reasoning, content creation, ethical judgment, and technology-supported learning indicate that it increasingly describes a context in which several competencies are enacted together. At the same time, constructs such as information literacy, computational thinking, critical thinking, creativity, and digital literacy retain distinctive conceptual properties, making their complete merger into a single generalized competence analytically problematic.

The pedagogical and assessment patterns reinforce the same interpretation. Multiple competencies can be activated within project-based, inquiry-oriented, collaborative, STEM/STEAM, game-based, makerspace, immersive, and digitally supported learning environments, yet they do not necessarily develop at the same rate or become observable through the same assessment approach. Work spanning inquiry learning, collaborative activities, computational thinking, design-oriented learning, and broader competency frameworks demonstrates that similar educational environments can combine multiple capabilities while retaining differences in their cognitive, interpersonal, and technical demands (Brieven et al., 2025; Chu et al., 2017; King & McCall, 2024; Shek et al., 2025).

Technological developments add further complexity to this structure. AI, robotics, digital transformation, data literacy, immersive technologies, and machine-learning-related concepts extend the contexts in which learners and educators engage with information, problems, communication, design, and decision making. Their increasing visibility does not establish a replacement hierarchy in which technologically newer competencies supersede established capabilities. Instead, they add new forms of activity in which foundational and specialized competencies increasingly intersect.

Taken together, the evidence indicates that the field is characterized by persistence, differentiation, and recombination. The 4Cs remain a stable conceptual foundation, while the environments in which they are enacted have expanded substantially through digital, informational, computational, and AI-mediated activities. The resulting digital competency ecosystem is therefore best understood as a relational structure in which established and newer competencies coexist, interact, and become increasingly specialized while retaining their conceptual distinctiveness.

CONCLUSION

Research on essential competencies in contemporary education has expanded substantially between 2015 and 2025 and has developed into a broad, interdisciplinary knowledge domain spanning STEM/STEAM, educational technology, teacher education, language learning, vocational education, assessment, sustainability, and digitally mediated learning. The bibliometric structure demonstrates that scholarly prominence within this field is multidimensional, as publication productivity, citation visibility, and network connectivity do not necessarily coincide. The literature is also internationally distributed but unevenly

connected, with substantial national concentrations of research activity and comparatively limited international co-authorship, indicating that competency research continues to be shaped by diverse institutional, curricular, technological, and geographical contexts.

The central conceptual finding is that critical thinking, creativity, communication, and collaboration remain persistent components of the contemporary competency landscape rather than being displaced by newer digital competencies. Digital literacy, digital competence, information literacy, computational thinking, data literacy, AI-related competence, and technology-supported learning increasingly intersect with the 4Cs and broaden the contexts in which these foundational capabilities are enacted. The temporal evidence further indicates increasing differentiation from broader notions of digital literacy toward more specialized areas involving digital skills, information and data literacy, digital competence, digital transformation, robotics, and AI-related learning. Contemporary competency research is therefore better characterized by integration, differentiation, and recombination than by a linear transition from traditional to digital competencies.

The resulting knowledge structure can be understood as a digital competency ecosystem in which established and emerging competencies coexist while retaining their conceptual distinctiveness. Pedagogical models, assessment practices, computational and collaborative learning, and STEM/STEAM environments form important connecting elements within this ecosystem, while AI, robotics, and other emerging technologies continue to expand its boundaries. These conclusions should nevertheless be interpreted within the methodological scope of the study, which was limited to English-language Scopus-indexed publications from 2015 to 2025 and was shaped by the selected search terms, full-counting procedure, keyword threshold, and bibliometric mapping settings. The identified relationships therefore represent patterns of scholarly attention, conceptual proximity, and thematic development rather than causal relationships among competencies or evidence of their comparative educational effectiveness.

RECOMMENDATION

Future research should prioritize the development and validation of integrated competency frameworks that preserve the conceptual distinctions among the 4Cs, digital competence, information literacy, computational thinking, AI-related competence, and other emerging capabilities while examining how they operate together in authentic learning contexts. Greater attention is needed to longitudinal and transfer-oriented studies that determine whether competencies developed through project-based, inquiry-oriented, STEM/STEAM, immersive, game-based, or AI-supported learning persist across time, disciplines, and professional settings. Assessment research should increasingly combine performance, process, and contextual evidence while addressing validity, fairness, transparency, privacy, and cross-cultural comparability. Curriculum and teacher-development initiatives should integrate digital, informational, computational, and ethical dimensions across disciplinary learning rather than treating them solely as isolated technical skills. Greater cross-national collaboration and validation are also needed to account for differences in infrastructure, culture, language, institutional capacity, and educational opportunity. Future bibliometric studies could strengthen the evidence base by incorporating additional databases, alternative counting procedures and thresholds, sensitivity analyses, and comparative mapping strategies to test the robustness of the competency structures identified in the present study.

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The authors have sufficiently contributed to the study, and have read and agreed to the published version of the manuscript.

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Declaration of Interest
The authors declare no conflict of interest.

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