



Review Article

Mapping Pre-Service Teachers' Digital Competence Research, 2014-2026: A Bibliometric Analysis of Conceptual Structure and Thematic Evolution

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ABSTRACT

Pre-service teachers' digital competence has become central to teacher education, yet the field's conceptual organization, international structure, and temporal development remain insufficiently integrated. This study maps the development of this research domain and identifies its publication patterns, collaboration networks, conceptual clusters, and emerging themes. A corpus of 582 English-language research and review articles published between January 2014 and 19 March 2026 was selected from the Web of Science Core Collection after screening 1,016 records. Bibliometrix/Biblioshiny and VOSviewer were used to analyze annual output, source- and country-level indicators, international co-authorship, author-keyword co-occurrence, overlay visualization, and thematic evolution. Publication output increased from 34 articles in 2020 to 120 in 2025, although productivity, citation visibility, and network connectivity produced different rankings. The United States contributed the most publications, whereas Indonesia recorded the highest international collaboration rate among the ten most productive countries. The keyword network comprised six clusters spanning professional preparation, technological pedagogical knowledge, ICT and digital skills, motivational and self-regulatory factors, data-related capabilities, and teacher training. Digital competence was the most frequent and connected keyword, followed by TPACK and pedagogical content knowledge. Temporal analyses showed persistent attention to digital competence, digital literacy, ICT, and TPACK, alongside the recent visibility of artificial intelligence, AI literacy, critical thinking, engagement, and pedagogical beliefs. These findings indicate cumulative thematic broadening rather than conceptual replacement. Future research should strengthen learner empowerment, performance-based assessment, responsible AI judgment, and longitudinal evidence linking competence development to instructional practice and learner outcomes.

KEYWORDS AI literacy • DigCompEdu • digital literacy • ICT integration • pedagogical beliefs • performance-based assessment • teacher education

ARTICLE CITATION

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1. INTRODUCTION

Digital transformation has reconfigured teachers' professional work by embedding digital platforms and data-intensive systems in lesson planning, classroom interaction, assessment, feedback, communication, and professional learning [1]. AI applications have extended this transformation by introducing new requirements for pedagogical decision-making and professional responsibility [2]. Professional digital competence therefore extends beyond device operation to encompass pedagogical judgment, critical resource evaluation, ethical and safe practice, and support for learners' digital agency [3]. This competence is particularly consequential in initial teacher education, where pre-service teachers develop the knowledge and professional routines required for digitally infused practice [4]–[7]. However, everyday technology use and exposure to educational software do not independently establish professional digital competence [8].

The construct itself requires conceptual precision. Digital literacy generally emphasizes the capacity to access, evaluate, create, and communicate through digital media, whereas technological pedagogical content knowledge (TPACK) explains how technological, pedagogical, and content knowledge interact in situated teaching [9], [10]. Teacher digital competence has a wider professional scope: it connects technical capability with pedagogical design, assessment, professional communication, learner inclusion, critical judgment, and ethical responsibility [3]. The European Framework for the Digital Competence of Educators (DigCompEdu) makes this scope explicit through 22 competences organized into six areas: professional engagement, digital resources, teaching and learning, assessment, empowering learners, and facilitating learners' digital competence [11], [12]. TPACK and DigCompEdu are consequently complementary rather than interchangeable. TPACK centers the knowledge configuration required for pedagogically meaningful technology integration, whereas DigCompEdu specifies a broader repertoire of educators' professional digital practices [1]. In the present study, digital competence is the focal construct. Digital literacy, information literacy, data literacy, technology integration, and AI literacy are treated as adjacent constructs whose relevance depends on their connection to professional teaching practice.

For pre-service teachers, digital competence develops through the interaction of coursework, teacher-educator modeling, design tasks, feedback, field experience, and institutional conditions. Evidence has repeatedly shown that isolated technology courses are insufficient when competence is not reinforced across methods courses and practicum settings [13]–[16]. Effective preparation tends to be coherent and iterative: pre-service teachers observe purposeful technology use, design technology-supported learning, enact plans in authentic contexts, reflect on outcomes, and revisit their

decisions with structured support [17]–[21]. Interventions informed by DigComp and DigCompEdu also show that targeted training can support development, although needs remain uneven across digital content creation, safety, assessment, and learner empowerment [22]–[24]. More recent intervention evidence also indicates that structured AI-integrated teacher education can contribute to AI literacy and digital material design competence [25]. Digital competence should therefore be understood as a developmental and context-dependent professional capacity rather than a stable personal attribute.

Empirical research has grown along several partially connected lines. One line examines competence levels, beliefs, and individual differences, often through DigCompEdu based self-report instruments [26]–[31]. A second investigates pedagogical integration through TPACK, coursework, lesson design, and field [19], [32]–[40]. A third evaluates how teacher education programs can cultivate digital competence through direct instruction, modeling, collaborative design, and authentic practice [20]–[22], [41]. The field has also expanded beyond general technology integration to data literacy, critical digital literacy, privacy, cybernetics, and responsible technology use [42]–[47]. AI adds a distinct layer to professional digital competence. AI literacy encompasses technical understanding, practical application, critical evaluation, creation, and ethical judgment [48], [49]. In teacher education, this construct extends to pedagogical integration, learner guidance, responsible decision-making, and the preservation of human agency [50], [51]. The resulting knowledge base is substantive but conceptually dispersed.

This expansion has exposed persistent problems of terminology and measurement. Digital competence, digital literacy, digital teaching competence, professional digital competence, ICT competence, and technology integration are frequently used with overlapping but non-equivalent meanings [3], [6], [10]. Even apparently specific components, such as digital resources, have been defined inconsistently across empirical studies [52]. Self-reported competence beliefs remain prominent, and recent syntheses identify continued variation in frameworks, instruments, samples, and research designs [30]. Because search terms, populations, and operational definitions vary, a conventional narrative synthesis cannot by itself reveal how these constructs cluster at field level, which themes occupy central or peripheral positions, or how their relative prominence changes over time.

Existing reviews have addressed important portions of this problem. Shokeen and Kaur [53] synthesized 21 empirical studies on factors influencing pre-service teachers' digital competence. Zeng et al. [54] reviewed 28 studies published from 2021 to 2025 to compare influencing factors, assessment frameworks, and international patterns, whereas Zhang et al. [55]

examined 38 studies from 2014 to 2024 to summarize trends, frameworks, methods, and limitations. These reviews clarify determinants and assessment practices but do not map the literature at corpus scale. Bibliometric studies provide a broader view. Marín-Suelves et al. [56] analyzed 150 Scopus records across school contexts, and Ma and Ismail [57] examined 1,054 Web of Science records across the wider educational domain. Their cross-population designs offer field-level coverage but cannot isolate patterns specific to pre-service teachers. Thuy et al. [58] narrowed the population and mapped 278 Scopus-indexed publications from 2009 to 2024, identifying publication growth, leading contributors, and four broad keyword-based research directions. That study did not combine its keyword mapping with periodized thematic evolution or interpretation through a professional competence framework.

The unresolved problem is therefore not an absence of research, but the lack of an integrated account of how this population-specific field is organized and how it has developed. Three gaps are consequential. First, broad bibliometric analyses combine teacher groups, learners, and educational levels, while population-specific systematic reviews contain too few records for stable science mapping. Second, the available pre-service-teacher bibliometric analysis describes contributors and broad directions but does not trace how thematic relationships reorganize across successive periods. Third, prior maps are primarily descriptive: keyword clusters have not been systematically interpreted against DigCompEdu, leaving the field's relative attention to professional engagement, digital resources, teaching and learning, assessment, learner empowerment, and the development of learners' digital competence insufficiently specified. This limitation becomes more salient as AI literacy, data literacy, and digital ethics enter the research agenda and potentially redraw its conceptual boundaries. Bibliometric science mapping can address these gaps by combining performance indicators with relational and temporal analyses of the research corpus [59].

This study analyzes 582 English-language research and review articles on pre-service teachers' digital competence indexed in the Web of Science Core Collection between January 2014 and March 2026, with 2026 treated as a partial year. Biblioshiny and VOSviewer are used to combine publication and source analysis, international collaboration mapping, author-keyword co-occurrence, overlay visualization, and thematic evolution. The study makes three contributions. It provides an updated, population-specific map of the field; explains the relationships and temporal movement among its principal themes; and uses DigCompEdu as an interpretive lens to identify concentrations and underrepresented areas within educators' professional digital competence. The analysis is guided by four research questions:

- RQ1: What patterns of publication growth and source-level citation visibility characterize research on pre-service teachers' digital competence?
- RQ2: How is research distributed across countries and regions, and what collaboration patterns characterize the international research network?
- RQ3: What major conceptual clusters and thematic relationships are reflected in the author keywords of this field?
- RQ4: How have the major research themes evolved over time, and what topics have recently emerged?

2. MATERIALS AND METHODS

2.1. Research Design

This study adopted bibliometric and network analysis methods to examine research on pre-service teachers' digital competence. Bibliometric analysis enables the quantitative examination of large-scale scientific literature and, when combined with statistical and network techniques, can be used to characterize research topics, structural relationships, and their development over time [59]–[61]. These methods are particularly suitable for identifying the conceptual structure of a research field, relationships among research topics, and changes in thematic patterns.

The analytical procedure followed the bibliometric framework proposed by Donthu et al. [59] and consisted of four stages: (a) defining the research scope, (b) determining the analytical methods, (c) collecting the data, and (d) conducting bibliometric and network analyses and integrating the results. The overall bibliometric analysis procedure is presented in Figure 1. To support transparency and reproducibility, the complete search strategy, screening records, keyword-cleaning procedures, analytical settings, VOSviewer files, Biblioshiny outputs, and sensitivity analysis results are available through the Open Science Framework (OSF) repository.

2.2. Search Scope and Strategy

The literature search was conducted in the Web of Science Core Collection on March 19, 2026, using the default coverage of its constituent indexes, including the Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI), Arts & Humanities Citation Index (A&HCI), Emerging Sources Citation Index (ESCI), Conference Proceedings Citation Index (CPCI), and Book Citation Index (BKCI).

The search strategy was structured around two principal concepts: pre-service teachers and digital competence. Digital literacy, information literacy, data literacy, technology integration, and DigCompEdu were included as supplementary retrieval concepts to increase coverage of relevant studies. These concepts were not

treated as synonyms of digital competence. Instead, they were regarded as theoretically related constructs representing different dimensions of pre-service teachers' digital capabilities and technology-related pedagogical practices.

Digital literacy, information literacy, and data literacy primarily concern capabilities related to

participation in digital environments, information processing, and data use. Technology integration concerns the knowledge and practices required to incorporate digital technologies into teaching, whereas DigCompEdu conceptualizes digital competence from the perspective of educators' professional practice.

Table 1. Web of Science Core Collection search strategy and database filters.

Database	Indexes	Search Date	Search Field	Population Terms	Digital Competence-Related Terms	Publication Period	Language	Document Types
Web of Science Core Collection	SCIE, SSCI, A&HCI, ESCI, CPCI, BKCI	March 19, 2026	TS = Topic	"preservice teacher" OR "pre-service teacher" OR "student teacher" OR "teacher candidate"	"digital competence" OR "digital literacy" OR "technology integration" OR "information literacy" OR "data literacy" OR "DigCompEdu"	January 2014–March 2026	English	Research articles and review articles

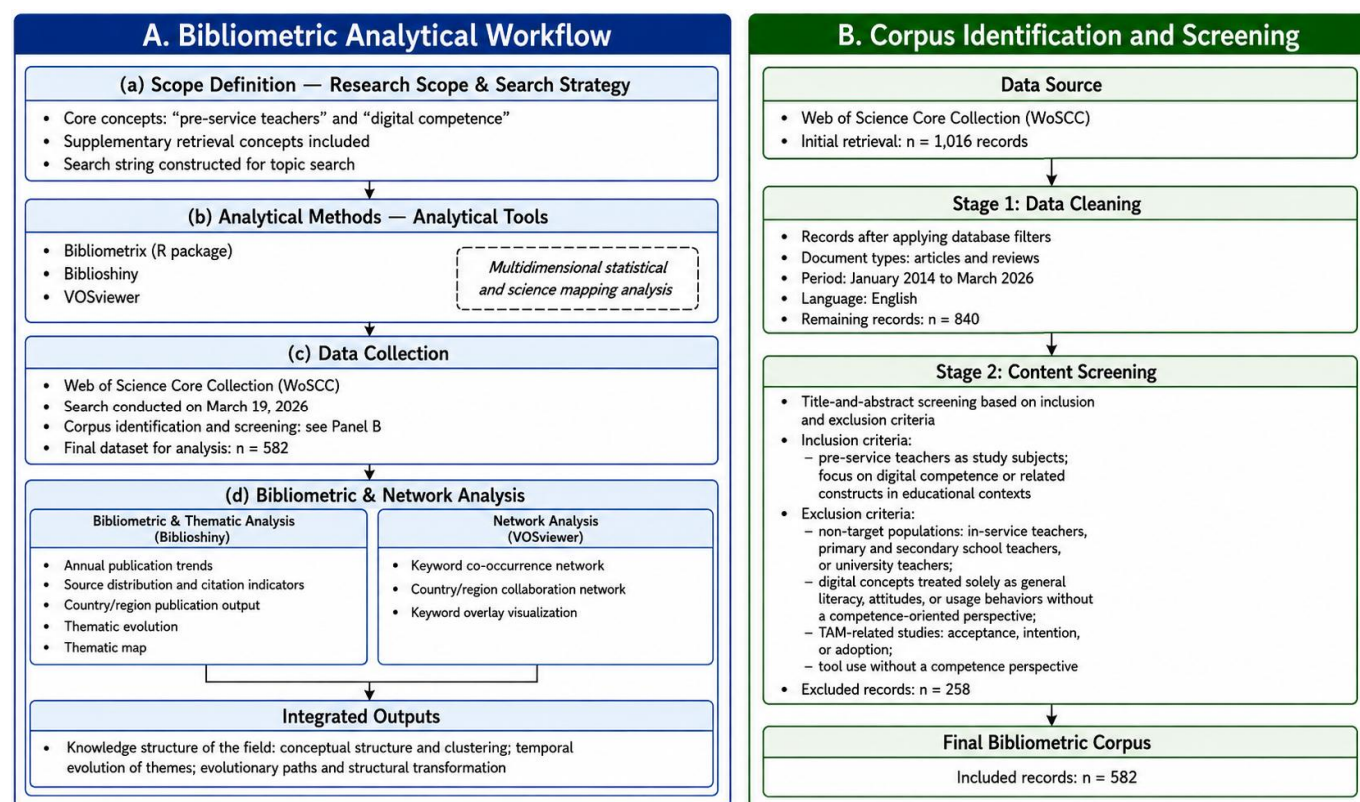


Figure 1. Bibliometric workflow and corpus selection.

Because studies on pre-service teachers use different terminology to describe related digital capabilities and technology-related pedagogical practices, a relatively broad retrieval strategy was applied to minimize the omission of potentially relevant publications. Subsequent title-and-abstract screening was used to ensure that the final corpus contained studies substantively related to pre-service teachers' digital competence or competence-related digital practices. Digital competence was retained as the central construct during keyword cleaning, cluster labeling, and interpretation, while conceptually related

terms remained differentiated according to their theoretical meanings.

2.3. Data Collection and Study Selection

The initial search identified 1,016 records. All records were exported from Web of Science in plain-text format using full records and cited references. The exported metadata included bibliographic information, abstracts, author keywords, Keywords Plus, source information, citation information, and cited references. No additional

database update was conducted after the final search date.

Study selection was conducted in two stages. In the first stage, database filters were applied to retain English-language research articles and review articles published between January 2014 and March 2026. The year 2014 was selected as the starting point because it followed the publication of the first European Digital Competence Framework and represents a period in which digital competence began to be discussed more explicitly as a structured competence construct in educational research. After these filters were applied, 840 records remained.

In the second stage, titles and abstracts were screened according to predefined inclusion and exclusion criteria. Studies were included when they focused on pre-service teachers and examined digital competence or related concepts from a competence-oriented perspective within educational contexts. Studies addressing digital literacy, information literacy, data literacy, technology integration, or DigCompEdu were retained when these concepts reflected competence-related knowledge, skills, practices, or pedagogical applications.

Studies were excluded when they: (a) examined non-target populations, including in-service teachers, primary and secondary school teachers, or university teachers; (b) examined digital technologies only as tools without addressing competence-related development or practice; (c) focused primarily on technology acceptance, intention, or adoption; or (d) treated digital concepts solely as general literacy, attitudes, or usage behaviors without a competence-oriented perspective.

A total of 258 records were excluded during content screening, resulting in a final bibliometric corpus of 582 documents. One researcher screened all titles and abstracts according to the predefined eligibility criteria. Records with uncertain eligibility were independently reviewed by a second researcher, and disagreements were resolved through discussion.

Table 2. Literature identification and selection process.

Stage	Procedure	Records
Initial identification	Web of Science Core Collection search	1,016
Database filtering	English research and review articles published January 2014–March 2026	840
Content screening	Records excluded based on predefined eligibility criteria	258 excluded
Final corpus	Documents included in bibliometric analysis	582

2.4. Data Preparation and Analytical Tools

Bibliometric analyses were conducted using the Bibliometrix package version 5.3.0 in R version 4.5.3, together with its web-based interface Biblioshiny [60].

VOSviewer version 1.6.20 was used for network construction and visualization [61].

Before keyword-based analyses were conducted, author keywords were cleaned and standardized to ensure consistency across analyses. The cleaning procedure involved merging synonyms, spelling variants, singular and plural forms, and closely related expressions referring to the same concept. The resulting standardized Author Keyword dataset was subsequently used in the relevant analyses performed with Biblioshiny and VOSviewer.

Biblioshiny was used to analyze annual publication trends, source distribution, and country/region-level publication output. It was also used to generate the thematic-evolution Sankey diagram and thematic map. VOSviewer was employed to construct and visualize keyword co-occurrence networks, country/region collaboration networks, and keyword overlay visualizations.

2.5. Network and Thematic Analysis

Keyword co-occurrence analysis was conducted using VOSviewer to map the conceptual structure of the field. The analysis used a minimum occurrence threshold of six, full counting, association-strength normalization, a clustering resolution of 1.00, and a minimum cluster size of one.

Country/region collaboration was examined through co-authorship analysis. The collaboration network used full counting, a minimum threshold of five documents per country/region, and association-strength normalization.

Keyword co-occurrence analysis was selected because it directly represents research themes and relationships among concepts appearing in the literature. In comparison, co-citation analysis primarily represents the intellectual foundations of a research field. Keyword co-occurrence analysis was therefore considered more appropriate for identifying the major themes and recent thematic developments examined in this study.

Temporal development was examined through keyword overlay visualization and thematic evolution analysis. The thematic evolution analysis was based on Author Keywords and divided the corpus into three periods. The thematic map was generated using 80 words and the Louvain clustering algorithm.

The integration of descriptive bibliometric statistics, keyword and collaboration networks, overlay visualization, and thematic evolution analysis provided complementary perspectives on the conceptual structure and thematic development of research on pre-service teachers' digital competence. Additional analytical resources are available through the OSF repository, while detailed parameter settings and sensitivity analysis results (Supplementary Table S1).

3. RESULTS

3.1. Corpus Characteristics, Publication Trends and Source-Level Citation Visibility

The final bibliometric corpus comprised 582 publications on pre-service teachers' digital competence published between January 2014 and March 19, 2026. The documents were distributed across 213 sources and involved 1,428 authors, with an average of 2.94 authors per document. The corpus contained 23,889 cited references and 1,427 author keywords.

Figure 2 presents the annual publication output. Publication volume remained relatively limited between 2014 and 2019, ranging from 9 to 18 publications per year. After 2019, output increased from 34 publications in 2020 to 56 in 2021, 63 in 2022, 93 in both 2023 and 2024, and 120 in 2025. Forty publications were indexed between January 1 and March 19, 2026. Because the 2026 value represents only a partial year, it was not compared directly with the complete annual totals. Based on the complete annual data through 2025, publication output increased substantially after 2020.

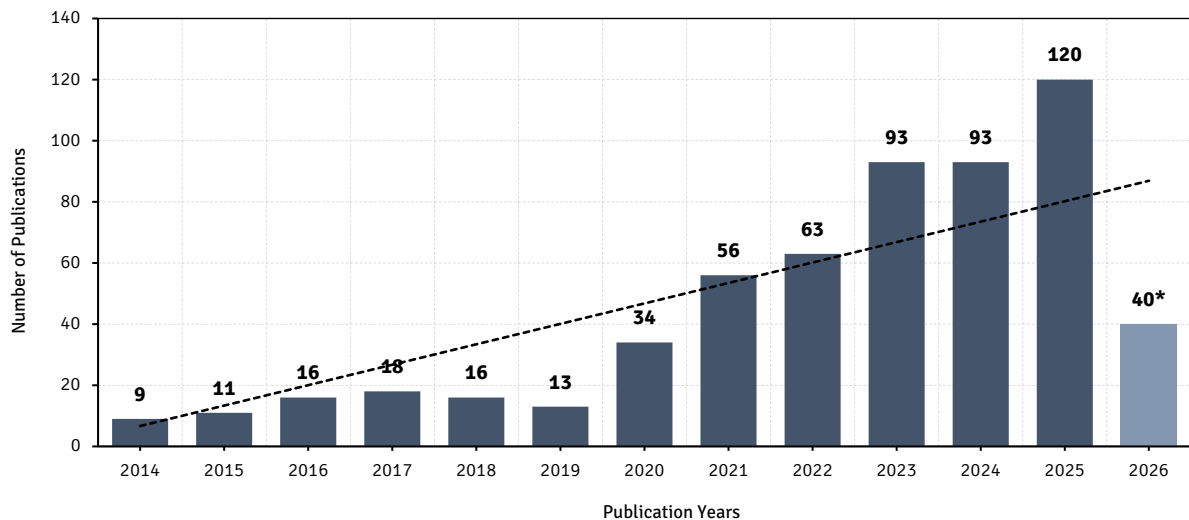


Figure 2. Annual publications (*March 19, 2026).

Table 3. Leading sources by publication volume and citation impact.

Sources (journal)	nd	GC	CPD	CPY	h-index
Education and Information Technologies	46	641	13.93	194.04	17
Education Sciences	34	320	9.41	90.70	8
Computers & Education	29	1662	57.31	260.79	19
Technology, Pedagogy and Education	16	183	11.44	23.70	8
Teaching and Teacher Education	15	496	33.07	59.94	8
Educational Technology Research and Development	14	808	57.71	114.57	11
Journal of Science Education and Technology	12	144	12.00	28.29	6
Frontiers in Education	12	67	5.58	23.44	5
European Journal of Teacher Education	11	562	51.09	205.45	8
Australasian Journal of Educational Technology	11	370	33.64	47.55	9

Note: nd = number of documents; GC = Web of Science Times Cited counts as of March 19, 2026; CPD = GC/nd; CPY is the sum of document-level annualized citation rates based on publication age; the h-index was calculated from the study corpus only. Citation indicators reflect citation impact rather than research quality and may be influenced by publication age.

Table 3 summarizes the ten sources with the largest publication output and their citation indicators. Education and Information Technologies contributed the largest number of documents (nd = 46), followed by Education Sciences (nd = 34) and Computers & Education (nd = 29). These journals therefore represented the largest publication outlets within the analyzed corpus.

Citation patterns differed from publication-volume rankings. Computers & Education recorded 1,662 global

citations and 57.31 citations per document, whereas Educational Technology Research and Development, with 14 documents, recorded 57.71 citations per document. Education and Information Technologies, despite contributing the largest number of publications, recorded 13.93 citations per document. These results indicate that publication volume and citation visibility followed different distributions across the leading sources, consistent with bibliometric guidance that distinguishes

productivity indicators from citation-based indicators in performance analysis [59]. The citation indicators reported here are descriptive and may be affected by publication age, database coverage, and indicator construction; they should therefore not be interpreted as direct measures of research quality [62].

3.2. Geographical Distribution and Collaboration

Table 4 presents publication output, citation indicators, and collaboration indicators for the ten countries/regions with the largest publication volume. The United States contributed the largest number of publications (nd = 128) and received the largest number of global citations (GC = 2,117). Türkiye ranked second in publication output (nd = 100; GC = 1,431), followed by Spain (nd = 63), Germany (nd = 53), and China (nd = 49). Average citation levels did not correspond directly to publication volume. Norway recorded the highest citations-per-document value among the listed countries (CPD = 60.52), followed by Australia (CPD = 32.88), despite their smaller publication counts of 23 and 33 documents, respectively.

The collaboration indicators also varied across countries. The United States recorded the largest total link strength (TLS = 34), followed by Türkiye (TLS = 29), Germany (TLS = 27), and China (TLS = 25). Indonesia showed the highest international collaboration rate among the ten countries (CR = 0.86), with a total link

strength of 15. In VOSviewer, total link strength represents the cumulative strength of an item's links with other items in the mapped network; accordingly, TLS is interpreted here as a structural connectivity indicator rather than as a measure of research quality [61]. Thus, publication volume, average citation frequency, international collaboration rate, and total link strength did not produce identical country rankings.

Table 4. Top 10 countries/regions by publication output, citation impact, and collaboration indicators.

Country	nd	GC	CPD	CR	TLS
USA	128	2,117	16.54	0.22	34
Türkiye	100	1,431	14.31	0.17	29
Spain	63	1,029	16.33	0.25	19
Germany	53	720	13.58	0.36	27
China	49	686	14.00	0.43	25
Australia	33	1,085	32.88	0.46	19
Norway	23	1,392	60.52	0.35	16
South Korea	17	404	23.76	0.41	7
Canada	15	120	8.00	0.40	6
Indonesia	14	94	6.71	0.86	15

Note: nd = number of documents; GC = global citations; CPD = citations per document; CR = international collaboration rate; TLS = total link strength.

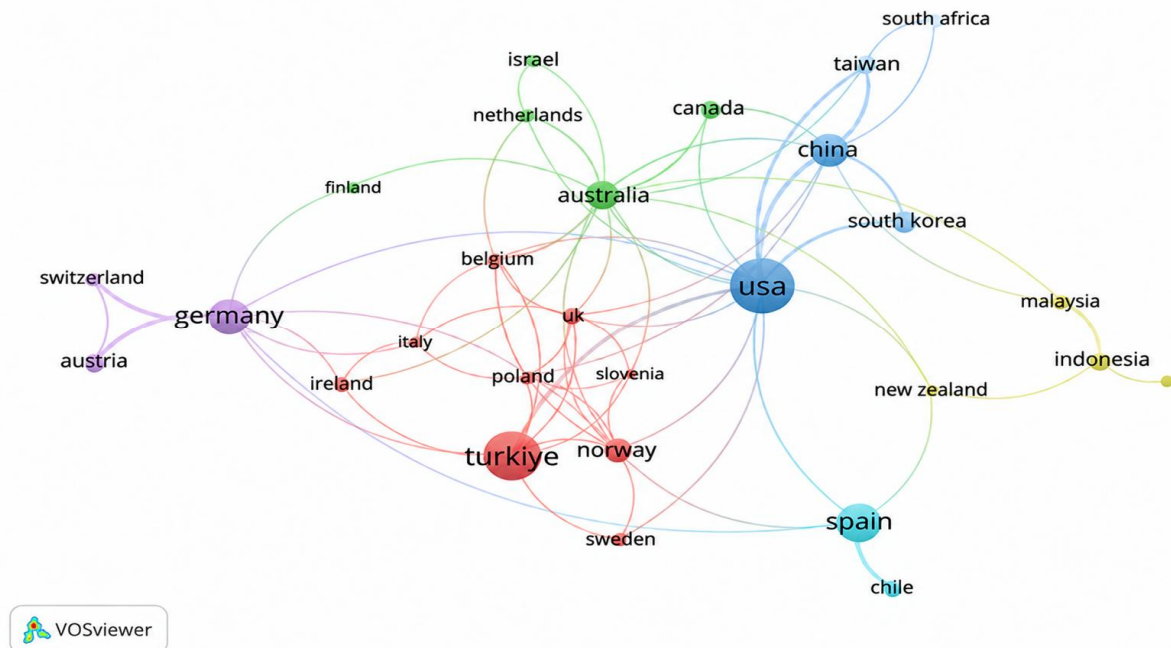


Figure 3. Country/region collaboration network. (node size: publications; edge width: collaboration strength; colors: clusters; full counting; minimum documents: 5).

The country/region collaboration network in Figure 3 shows several interconnected groups. The United States and Türkiye were associated with comparatively high total link strength, while Germany and China also displayed multiple international collaboration links. Indonesia

combined a comparatively high international collaboration rate with a total link strength of 15. The visualization therefore complements the quantitative indicators in Table 2 by showing how international co-authorship links were distributed across the network.

3.3. Keyword Co-Occurrence Analysis

Keyword co-occurrence analysis was conducted using the cleaned author keywords of the 582 publications. With a minimum occurrence threshold of six, the resulting VOSviewer network consisted of six clusters. Digital competence had the highest occurrence frequency (n = 380) and total link strength (TLS = 614), followed by

TPACK (n = 147, TLS = 349), pedagogical content knowledge (n = 134, TLS = 339), teacher education (n = 125, TLS = 232), ICT (n = 85, TLS = 190), and self-efficacy (n = 82, TLS = 209). These terms were the most frequently occurring and strongly connected author keywords according to the occurrence and TLS indicators used in the analysis.

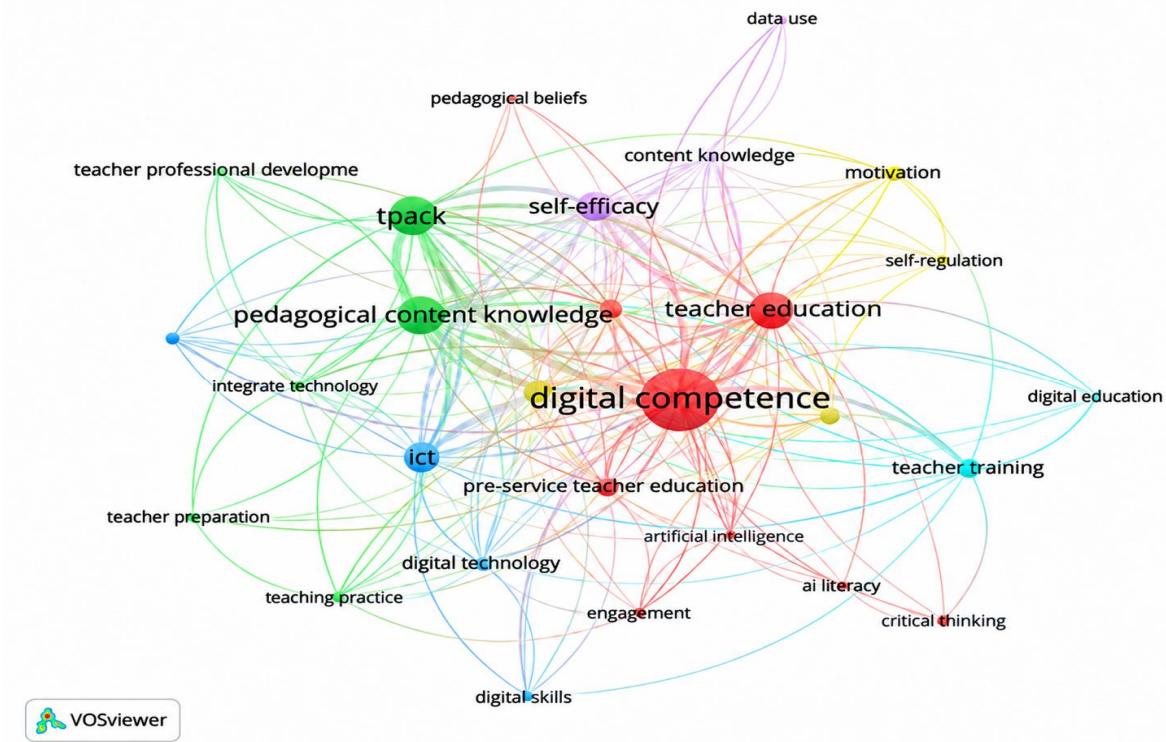


Figure 4. Author-keyword co-occurrence network. (node size: occurrences; edge width: co-occurrence strength; colors: six clusters; full counting; minimum occurrence: 6).

Six descriptive cluster labels were assigned based on the dominant keywords, keyword frequency, total link strength, and thematic relationships within each cluster. Cluster 1, Teacher Education and Digital Competence, included digital competence, teacher education, pre-service teacher education, professional development, pedagogical beliefs, engagement, critical thinking, artificial intelligence, and AI literacy. Cluster 2, Technology Integration and Pedagogical Knowledge, included TPACK, pedagogical content knowledge, technology integration, teacher preparation, teacher professional development, and teaching practice. Cluster 3, ICT and Digital Skills, included ICT, digital technology, digital skills, and initial teacher education.

Cluster 4, Attitudes, Motivation, and Self-Regulation, comprised attitudes, motivation, self-regulation, and educational technology. Cluster 5, Self-Efficacy and Data-Related Factors, included self-efficacy, content knowledge, and data use. Cluster 6, Digital Education and Teacher Training, was mainly represented by digital education and teacher training. The labels summarize co-occurrence patterns and should not be treated as empirically validated competence dimensions or as evidence of causal relationships among the included concepts. This labeling approach is consistent with science-mapping practice in which algorithmically detected clusters are interpreted through their dominant terms and relational structure, while the resulting labels remain descriptive analytical summaries [59], [63].

Table 5. VOSviewer author-keyword clusters and representative standardized terms at a minimum occurrence threshold of six.

Cluster	Descriptive label	Representative terms
1	Teacher Education and Digital Competence	digital competence; teacher education; pre-service teacher education; professional development; pedagogical beliefs; engagement; critical thinking; artificial intelligence; AI literacy

Cluster	Descriptive label	Representative terms
2	Technology Integration and Pedagogical Knowledge	TPACK; pedagogical content knowledge; technology integration; teacher preparation; teacher professional development; teaching practice
3	ICT and Digital Skills	ICT; digital technology; digital skills; initial teacher education
4	Attitudes, Motivation, and Self-Regulation	attitudes; motivation; self-regulation; educational technology
5	Self-Efficacy and Data-Related Factors	self-efficacy; content knowledge; data use
6	Digital Education and Teacher Training	digital education; teacher training

3.4. Temporal Evolution and Thematic Configuration

Three complementary analyses were used to characterize the temporal structure of the corpus: keyword overlay visualization, thematic evolution analysis, and thematic mapping. Figure 5 presents the temporal distribution of author keywords, Figure 6 traces thematic continuity and change across three periods, and Figure 7 positions current themes according to centrality and density. Combining these views is consistent with longitudinal science-mapping approaches that distinguish current network structure from temporal reconfiguration of themes [60], [63].

Figure 5 presents the temporal distribution of keywords in the co-occurrence network. Earlier average publication years were observed for keywords including

ICT, pedagogical content knowledge, TPACK, and technology-integration-related terms. More recent average publication years were observed for artificial intelligence, AI literacy, critical thinking, digital skills, engagement, and pedagogical beliefs. According to the VOSviewer item-level data, these more recent keywords had average publication years ranging from 2023.27 to 2024.83 and total link strength values ranging from 9 to 22. Overlay visualization is used here to represent the relative temporal position of items within an existing network rather than to establish the origin or causal growth of a topic [61]. These values therefore indicate comparatively recent visibility within the analyzed network; they do not, by themselves, establish long-term growth or the formation of independent research domains.

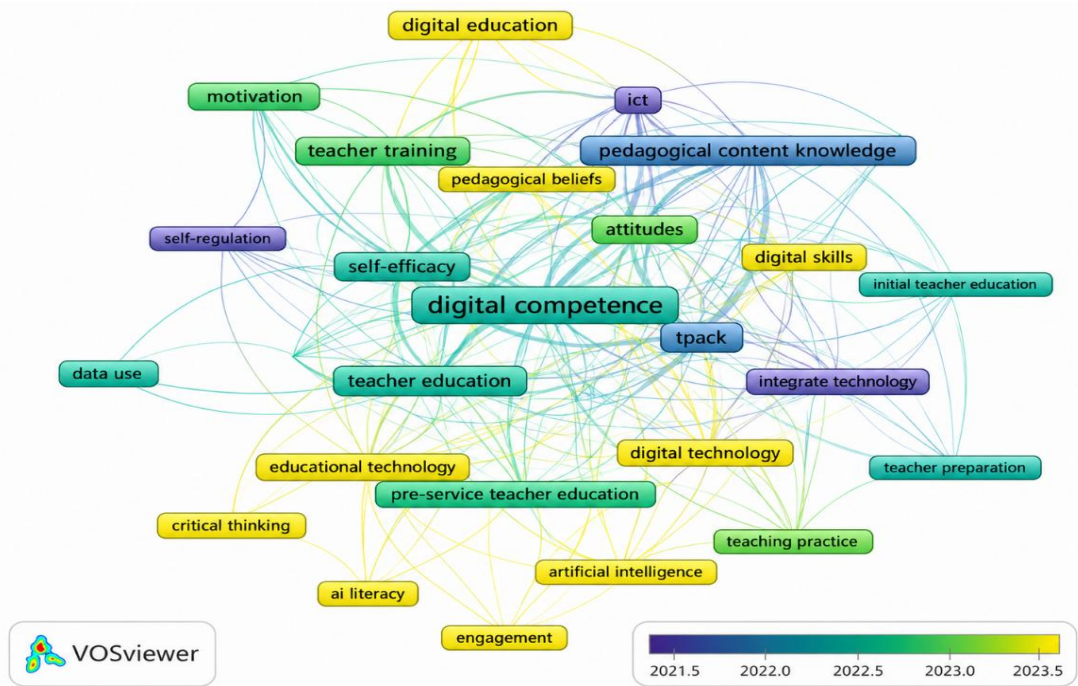


Figure 5. Keyword co-occurrence over time (node color indicates average publication year).

Figure 6 presents thematic evolution across three periods: 2014–2020 (n = 117), 2021–2023 (n = 212), and 2024–2026 (n = 253). The final period includes records indexed only through March 19, 2026 and should therefore be interpreted as a partial-period representation. During 2014–2020, the identified themes included digital

competence, ICT, data literacy, digital literacy, technology integration, information literacy, and student teaching. During 2021–2023, digital competence and digital literacy remained represented, while TPACK, technology integration, educational technology, initial teacher education, self-efficacy, digital technology, pre-

service teacher education, teacher preparation, and pre-service teacher training were also identified. During 2024–2026, the thematic structure included digital competence, TPACK, digital technology, digital literacy, pre-service teacher education, initial teacher education,

and motivation. The longitudinal co-word approach underlying thematic-evolution analysis is specifically designed to trace continuity, transformation, and reconfiguration of themes across successive time slices [64].

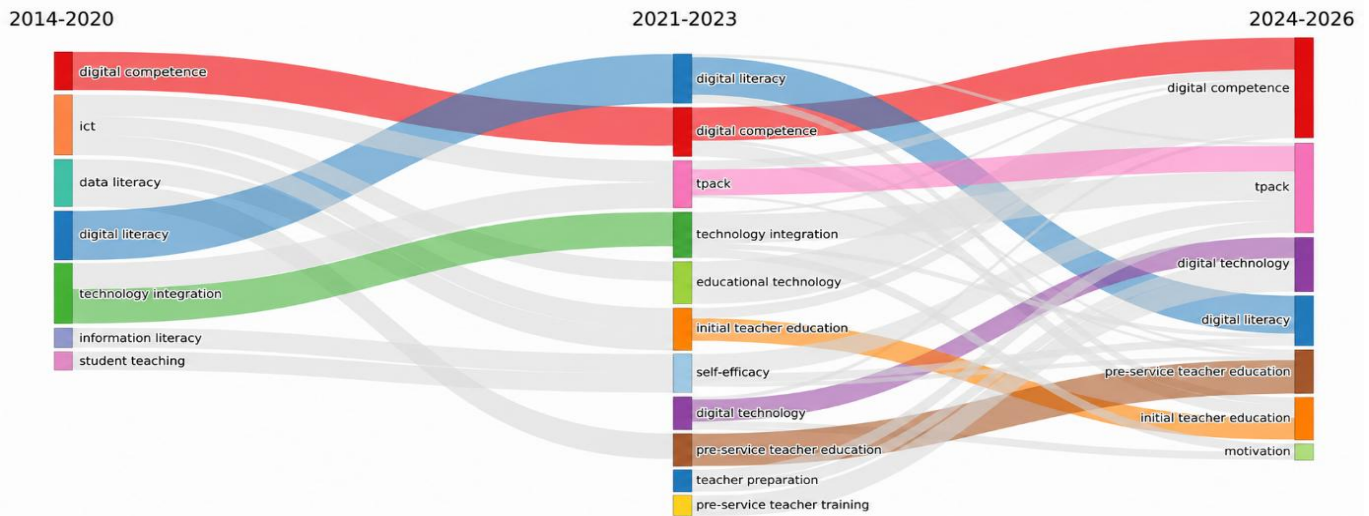


Figure 6. Thematic evolution (node height: theme frequency; flow width: weighted inclusion index; Louvain clustering; minimum cluster frequency: 5 per thousand documents).

Digital competence was represented across all three periods and showed the largest theme frequency in the most recent period. Sensitivity analyses indicated that the principal themes remained stable under an alternative period division. AI literacy also remained visible after exclusion of the 40 partial-year 2026 records, although its

temporal placement shifted to the 2022–2025 period under the alternative division. These sensitivity results support the stability of the principal thematic pattern while showing that the temporal placement of a recent, low-frequency theme may depend on period specification.

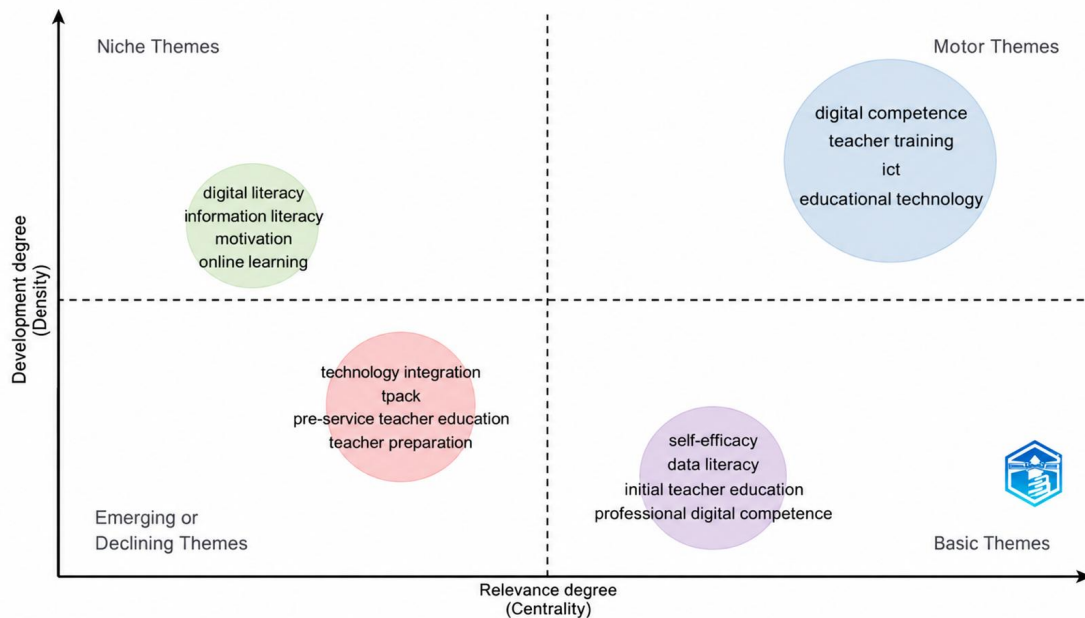


Figure 7. Thematic map by keywords (node size: theme frequency; quadrants: centrality and density; Louvain clustering; minimum cluster frequency: 10 per 1,000 documents).

TPACK, technology integration, pre-service teacher education, and teacher preparation occupied the lower-left quadrant, which is conventionally described as

containing emerging or declining themes in strategic co-word diagrams [64], [65]. Quadrant position alone, however, does not establish whether a theme is emerging

or declining because the same low-centrality/low-density position can characterize themes at different stages of a thematic trajectory. The overlay visualization and thematic-evolution results therefore provide the temporal information required to interpret these positions [64]. In the present corpus, these complementary analyses show that TPACK and technology integration persisted across multiple periods rather than representing exclusively recent developments.

Across the four research questions, three descriptive patterns were identified. First, publication output increased after 2020, while publication volume and citation indicators varied across sources and countries. Second, the author-keyword network was organized into six clusters spanning digital competence, pedagogical knowledge and technology integration, ICT and digital skills, psychological factors, data-related themes, and teacher training. Third, the temporal analyses showed continuity in established themes such as digital competence and TPACK alongside the comparatively recent visibility of AI-related keywords. These findings describe the publication, network, and thematic structure of the analyzed Web of Science corpus and should not be interpreted as direct evidence of changes in pre-service teachers' actual competence, instructional effectiveness, or causal relationships among the identified concepts.

4. DISCUSSION

The bibliometric evidence supports four connected interpretations. Publication activity expanded rapidly after 2020, but output, citation visibility, and international connectivity remained distinct dimensions. Digital competence was increasingly positioned within teacher education and professional preparation rather than operational technology use. TPACK, foundational digital literacies, self-efficacy, and data use retained different structural roles within a broader construct of professional digital competence. Learner empowerment, performance-based assessment, and responsible artificial intelligence (AI) remained comparatively weak or emergent. These findings describe publication and keyword structures; they neither demonstrate longitudinal improvement in pre-service teachers' competence nor establish the causal effectiveness of a training model.

4.1. Growth, Citation Visibility and Collaboration

Annual output increased from 34 records in 2020 to 120 in 2025, indicating sustained expansion of the research domain. Bibliometric reviews identify broad growth in digital-competence research [56], while population-specific reviews report greater attention to teacher education and professional preparation [58], [66]. The increase cannot be attributed exclusively to COVID-19 because policy reform, framework diffusion, database

coverage, and maturation of educational technology research may also explain it. Starkey [6] had identified digital-age teacher preparation as a distinct concern before emergency remote teaching. The 40 records indexed by March 19, 2026, represent continuing activity rather than a complete annual observation.

Publication volume and influence followed different distributions. Education and Information Technologies produced the most documents, whereas Computers & Education received the most citations and a higher citation rate per document. Citation counts indicate scholarly visibility, not methodological quality, because they vary with publication age, database coverage, document type, and field size [59]. The United States and Türkiye combined productivity with network centrality; Australia and Norway achieved higher average citation visibility with fewer papers; Indonesia recorded the highest international collaboration rate and a bridging position relative to its output. These distinctions separate productivity, impact, and brokerage. English-language Web of Science coverage and full counting may underrepresent local scholarship and credit each partner fully, so future comparisons should incorporate regional databases and fractional counting.

4.2. Professionalization of Digital Competence in Teacher Education

Keyword centrality and proximity to teacher education, professional development, pedagogical beliefs, critical thinking, and AI literacy position digital competence as a component of professional formation. DigCompEdu encompasses professional engagement, resources, teaching, assessment, learner empowerment, and facilitation of learners' digital competence [12]. Falloon's [3] framework similarly integrates technical capability with pedagogical, ethical, personal, and professional judgment. Frameworks developed for practicing teachers can inform initial teacher education, but they require adjustment to beginning teachers' developmental position and responsibilities [7]. The observed network therefore suggests professionalization: digital capability is associated with what teachers know, how they design instruction, and how they exercise judgment in digitally mediated settings [26], [67], [68].

Temporal change reflects accumulation rather than replacement. ICT, digital literacy, information literacy, and data literacy remained foundational as initial teacher education, TPACK, and professional digital competence gained prominence. Teacher-educator modelling and authentic practice support this integration [16], [41], while design tasks, collaboration, and reflection strengthen the transfer of digital knowledge into teaching practice [18], [35], [36], [69]. Recent syntheses similarly emphasize enacted teaching and sustained professional engagement [20], [40].

DigComp- and DigCompEdu-based studies further frame digital competence as a multidimensional

professional capability developed through authentic application. Getenet et al. [17] and Luís and Rodrigues [24] support linking competence frameworks with practice, while related studies reinforce their contextual application in teacher education [21]–[23]. Coursework alone is insufficient because field experiences and beliefs also shape technology use [19]. Thematic change therefore represents the progressive integration of foundational digital literacies into pedagogical and professional practice.

At the program level, competence should be distributed across coursework and practicum rather than confined to a stand-alone technology course. Cross-national expert evidence identifies curriculum requirements involving digital-content management, subject-specific integration, data protection, e-risks, accessibility, and advanced competence [70]. A developmental sequence can establish foundational practices, require subject-specific resource evaluation and lesson design, test these decisions during supervised teaching, and use performance evidence for reflection. Alignment among course outcomes, practicum expectations, assessment criteria, mentor feedback, and teacher-educator modelling is required to prevent isolated technical proficiency from being misclassified as professional competence.

4.3. TPACK, Motivational Conditions and Measurement

TPACK remained a frequent and well-connected theme, particularly in relation to pedagogical content knowledge, technology integration, teacher preparation, and teaching practice. As formulated by Mishra and Koehler [9], TPACK explains the interaction among technological, pedagogical, and content knowledge required for subject-specific instructional design. Its continued relevance has been reinforced in studies of teacher education, technology integration, and instructional planning [37]–[39], [71], [72]. These findings indicate that TPACK remains a specialized framework for understanding technology-supported teaching rather than a general model of teachers' digital capability.

Professional digital-competence frameworks have a broader scope, covering professional engagement, digital-resource management, assessment, inclusion, learner empowerment, and continuing development [1], [3], [12]. Pettersson [10] further shows that digital competence is influenced by organizational and policy contexts beyond classroom instruction. TPACK and professional digital competence are therefore complementary rather than interchangeable constructs [73]. Its lower-left thematic-map position should not be interpreted as decline, but more plausibly as conceptual diffusion or peripheral specialization within a broader professional digital-competence discourse.

Links among self-efficacy, attitudes, motivation, self-regulation, and pedagogical integration identify enabling conditions rather than competence itself [74]–

[78]. ICT self-efficacy has been reported to mediate much of the association between university ICT support and TPACK [66], while online self-regulated learning strategies have mediated the association between integration self-efficacy and ICT competence [66]. These studies support theoretically specified mechanisms, but the present co-occurrence network tests neither mediation nor temporal order. Keyword proximity only indicates joint attention within publications. Subsequent research should separate knowledge, motivation, design quality, classroom enactment, and learner outcomes because change in one domain does not establish change in another.

Digital, information, and data literacies occupied distinguishable network positions, supporting conceptual differentiation. Foundational literacies concern access, interpretation, creation, communication, and safe participation; professional digital competence applies those capabilities to defensible educational decisions [79]. Resource selection, for example, additionally requires attention to learning goals, learner characteristics, copyright, privacy, and pedagogical fit [12], [52]. Data literacy appeared as a basic but internally weak theme [80]. Intervention studies show that data knowledge and attitudes can improve without equivalent growth in motivation to use data [46], [81], supporting separate measurement of cognitive and motivational outcomes.

The prominence of self-efficacy and self-perceived competence also exposes a measurement constraint. Validated DigCompEdu instruments characterize beliefs and developmental profiles but do not directly establish performance [30]. Rubric-based assessments, authentic tasks, and observed teaching provide complementary evidence of resource selection and subject-specific application [82], [83]. Increases in self-assessment should consequently be reported as changes in perceived competence unless corroborated by performance data. Cross-national comparisons additionally require measurement-invariance testing and control for infrastructure, curriculum, language, practicum access, and policy context.

4.4. Learner-Oriented Competence and Responsible AI

The limited recurrence of accessibility, differentiation, learner agency, and learners' digital competence identifies an underdeveloped learner-oriented domain. Failure to meet a keyword threshold does not prove absence; it indicates that these constructs were insufficiently recurrent to organize the network. This imbalance matters because DigCompEdu explicitly includes learner empowerment and facilitation of learners' digital competence, covering inclusion, personalization, information evaluation, content creation, responsible use, and problem solving [12]. Responsible ICT research similarly connects teacher preparation with digital citizenship, privacy, and safe participation [8], [84], [85]. Future mapping should use lower thresholds and

content analysis to determine whether learner-oriented constructs are present under heterogeneous terminology.

The AI-related terms indicated emergence rather than maturity. Artificial intelligence, AI literacy, critical thinking, and engagement had recent average publication years but modest link strengths and no independent cluster. Initial interventions indicate that generative-AI competence includes evaluation of output quality, pedagogical appropriateness, and instructional design, not prompt execution alone [50]. Pre-service teachers' AI literacy is also associated with knowledge, attitudes, and prior use of AI-enabled applications [49]. UNESCO organizes teacher AI competence around a human-centered mindset, ethics, foundations and applications, pedagogy, and professional learning [2]. Training centered on ethics and human-centered reflection may develop judgment not captured by tool-focused confidence [86].

Responsible AI should therefore be integrated across pedagogy, assessment, academic integrity, privacy, accessibility, and data governance. Research should assess whether pre-service teachers can identify inaccurate or biased outputs, disclose assistance, protect learner data, preserve agency, and justify when non-AI methods are preferable. Effects on learners with disabilities, limited connectivity, minoritized languages, or unequal access to paid systems also require evaluation. These questions connect the emerging AI theme to the learner-empowerment gap and require evidence from observed decisions and consequences rather than acceptance, intention, or self-reported confidence.

4.5. Theoretical Contribution, Practical Implications and Research Priorities

The six clusters can be interpreted as a layered conceptual structure. Digital, information, and data literacies provide enabling capabilities; TPACK supplies a subject-specific knowledge architecture; motivation, self-efficacy, and self-regulation condition engagement; DigCompEdu domains describe professional enactment; and AI literacy adds ethical and epistemic governance. This structure is an authorial inference from co-occurrence and temporal evidence, not a tested causal model. Its analytical value lies in connecting related constructs without collapsing them into one score.

Temporal evidence supplies a second contribution. Digital literacy was not replaced by TPACK, nor was TPACK replaced by AI literacy. Established concepts persisted while their professional context broadened. This cumulative pattern explains why technology-integration terms can appear peripheral on a current map while remaining historically consequential. Curriculum priority should therefore be determined by professional relevance, not thematic novelty; resource evaluation, subject-specific pedagogy, privacy, assessment, and inclusion remain necessary when new tools emerge.

Four program implications follow from the combined evidence. Competence outcomes should be mapped across all DigCompEdu areas and sequenced through coursework and practicum. Teacher educators and mentors should model explicit decisions to select, adapt, or reject digital tools. Assessment should combine validated self-report measures with knowledge tests, artefact rubrics, scenario-based tasks, and observed teaching. AI outcomes should be embedded within existing expectations for pedagogy, ethics, privacy, accessibility, assessment, and professional learning. These actions organize preparation around durable professional judgment instead of transient tool familiarity.

Research priorities should move beyond descriptive profiles. Longitudinal and intervention designs are needed to evaluate development across coursework, practicum, and entry into teaching. Multilevel analyses should distinguish individual factors from program, institutional, and policy conditions, while performance indicators should be linked to instructional quality and learner outcomes. Reliability, validity, and measurement invariance require explicit testing. Qualitative analysis of lesson designs, classroom decisions, and ethical dilemmas can identify mechanisms not observable in bibliometric networks. Cross-regional studies should include underrepresented publication systems and assess whether bridging collaborations produce shared instruments, reciprocal capacity, and locally relevant evidence. The field has achieved conceptual breadth, but learner empowerment, performance-based assessment, and responsible AI require more coherent empirical development.

5. CONCLUSION AND LIMITATIONS

Research on pre-service teachers' digital competence expanded substantially after 2020 and developed differentiated publication, collaboration, and conceptual structures. Publication volume, citation visibility, and international network position did not coincide, demonstrating that productivity, scholarly influence, and collaboration brokerage represent distinct dimensions of field development. The six keyword clusters position digital competence as a professional construct integrating foundational digital literacies, TPACK, teacher preparation, technology integration, psychological factors, and data-related capabilities. Temporal patterns indicate cumulative thematic broadening: ICT, digital literacy, and TPACK persisted while professional digital competence and AI-related themes gained visibility. Viewed through DigCompEdu, this development remains uneven. Teacher preparation and pedagogical integration are relatively established, whereas learner empowerment, digitally supported assessment, and responsible AI judgment require further conceptual and empirical development.

Four limitations delimit these interpretations. The exclusive use of the Web of Science Core Collection may have omitted relevant studies indexed elsewhere and affected geographic and thematic representation. The search strategy combined related but theoretically distinct constructs, increasing coverage while introducing conceptual heterogeneity. Although sensitivity analyses indicated general stability, narrower construct-specific corpora should be compared. Bibliometric indicators capture publication activity, intellectual structure, and keyword relationships, not actual changes in pre-service teachers' competence or the effectiveness of specific interventions. Future studies should integrate bibliometric mapping with systematic content analysis, performance-based assessment, and longitudinal or intervention designs. The incomplete 2026 dataset also makes the most recent thematic patterns provisional; these patterns should be reassessed after full-year indexing.

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CONFLICTS OF INTEREST

The authors declare that no conflicts of interest are associated with this study. All aspects of the research were conducted with the utmost integrity and transparency.

DATA AVAILABILITY

The supplementary materials related to this study are available on the Open Science Framework (OSF) <https://doi.org/10.17605/OSF.IO/TD489>

ETHICAL STATEMENTS

Not applicable. This study did not involve any human participants or animals, and no personal or sensitive data were collected, used, or analyzed at any stage of the research.

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