

Global Landscape of Teacher Digital Competence Research: Collaboration Networks, Thematic Clusters, and Emerging Frontiers

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ABSTRACT: To address the gaps in existing research on Teacher Digital Competence (TDC) such as fragmented themes, limited sample scope, and insufficient cross-contextual insights, this study systematically maps the evolutionary landscape of TDC research during 2016–2025 through a mixed-methods approach integrating bibliometric analysis and qualitative synthesis. Based on 2,227 valid publications retrieved from Web of Science and Scopus, the study explores cross-national collaboration patterns, core themes, and emerging frontiers of TDC research. Results show that TDC research has grown robustly, with Spain leading in publication volume and Australia acting as a pivotal hub for global collaboration, while research output is concentrated in high- and upper-middle-income countries. The intellectual structure of the field is consolidated into five interconnected thematic domains: Competence Dimensions and Frameworks, Teacher Education and Professional Development, Curriculum Integration and Digital Pedagogy, Domain-Specific Adaptation, and Artificial Intelligence Competence. Research frontiers have evolved from conceptual foundation and technology integration to pandemic response, and currently focus on distance learning and AI competence. Theoretically, this study provides a holistic, decadal-scale mapping of TDC research, advancing the understanding of TDC as a context-dependent construct. Practically, it offers evidence-based guidance for policymakers, educational institutions, and researchers, while highlighting the need to address regional disparities and explore under-explored areas such as TDC in resource-constrained contexts.

KEYWORDS - teacher digital competence; bibliometric analysis; CiteSpace; teacher training

I. INTRODUCTION

The rapid advancement and widespread adoption of digital technologies have precipitated a paradigm shift in global education systems. The growing accessibility of digital tools, media, and resources has positioned the integration of digital technology and pedagogy as a key driver of instructional innovation, thereby continually reshaping teaching practices [1]. Against this backdrop, Teacher Digital Competence (TDC) has emerged as a foundational competency for educators in the digital age, widely recognized as critical to enhancing instructional quality and empowering student development. However, extant research consistently highlights a notable gap between the required level of TDC for effective digital teaching and teachers' actual capabilities [2], underscoring the urgency of conducting in-depth investigations into this area.

Scholarly interest in TDC has expanded exponentially in response to this pressing need, with existing studies evolving around three core strands: conceptual clarification, empirical assessment, and practical improvement. Conceptually, "digital competence" and "digital literacy" were once used interchangeably, resulting in

disciplinary ambiguity [3]. Originating in the late 1990s as a skill-oriented construct centered on the utilization of digital resources [4], the concept has undergone a paradigmatic shift toward a holistic notion of “digital competence”—one that integrates sociocultural, ethical, and intentional dimensions beyond mere technical operation [5]. TDC specifically denotes a dynamic, multidimensional system of skills, attitudes, and knowledge that enables educators to thrive in digital environments, leverage technology to enhance teaching quality, and equip students for a digital society [6].

Empirically, existing studies cover a diverse range of themes: the evolution of TDC concepts before and after the pandemic [7]; automated methods based on Learning Management Systems (LMS)[8]; the development of TDC among and in-service teachers [9]; domain-specific adaptations in STEM education [10] and higher education contexts [11]; as well as focused explorations of specific dimensions, such as digital security [12]. Methodologically, systematic literature reviews remain the dominant approach [13], while bibliometric analyses have recently gained traction [14], providing macro-level insights into the field. However, most of systematic reviews are still constrained by small, context-specific samples or a focus on single dimensions [15].

Despite these advancements, the existing body of research still exhibits several notable limitations. First, systematic literature reviews frequently rely on small, context-specific samples and focus on isolated themes, which prevents them from capturing cross-contextual trends and the holistic intellectual structure of the field. Second, significant regional disparities persist: most research is concentrated in developed countries (e.g., Spain, China, and the United States), while resource-constrained contexts are largely overlooked [16]. Finally, emerging themes—such as the application of artificial intelligence in teaching [17] and the intersection of TDC with distance learning in the post-pandemic era—require more systematic synthesis to identify coherent research frontiers.

To address these gaps, the present study aims to answer two core research questions: (1) What is the scholarly landscape and the pattern of cross-national collaboration in TDC research over the past decade (2016–2025)? (2) What constitutes the core research themes, their interconnections, and emerging frontiers in the field of TDC?

To achieve these objectives, we employed a mixed-methods approach that combines bibliometric analysis and qualitative synthesis. Practically, the findings provide actionable guidance for policymakers to design evidence-based digital education strategies, for educational institutions to refine pre-service and in-service TDC training programs, and for researchers to identify underexplored domains such as distance learning-related competencies. Furthermore, the study’s focus on global and regional disparities facilitates targeted interventions to mitigate digital divides, thereby supporting the sustainable development of inclusive education systems worldwide. Collectively, this work functions as a foundational reference for advancing both academic scholarship and educational practice amid the ongoing digital transformation of global education.

II. METHODS

2.1 Data Collection and Screening

2.1.1 Database Selection

To guarantee the comprehensiveness, authority, and cross-disciplinary coverage of the literature sample, this study chose two leading academic databases—Web of Science (WOS, Core Collection) and Scopus—as its data sources. These two databases are widely acknowledged for their rigorous indexing criteria, frequently adopted as primary data repositories in review studies [18]. Their combined use mitigates the risk of literature omission and improves the representativeness of the research sample.

2.1.2 Retrieval Strategy Development

A two-stage retrieval strategy was developed based on the core connotations of Teacher Digital Competence (TDC). The initial search string, designed from core TDC concepts, was found to lack precision and missed dimensions. To address this, the strategy was refined by incorporating keywords derived from the EU’s DigCompEdu framework [19]—a benchmark model widely validated in TDC research [20] and applying proximity operators (NEAR/3 in WOS, W/3 in Scopus) to ensure close contextual association between core concepts, as detailed in Table 1.

Table 1 Four retrieval strategies

Number	Search string	Number of articles	
		WoS	Scopus
1	("digital competenc*" OR "digital literacy" OR "digital skill*") NEAR/3 ("teacher*" OR "educator*" OR "faculty")	532	2536
2	("digital pedagogy" OR "technology-enhanced learning" OR "e-assessment") NEAR/3 ("teacher*" OR "educator*" OR "faculty")	62	324
3	("digital ethics" OR "digital safety" OR "data protection" OR "cybersecurity") NEAR/3 ("teacher*" OR "educator*" OR "faculty")	18	147
4	("digital resource*" OR "educational technology" OR "ICT resource*") NEAR/3 ("teacher*" OR "educator*" OR "faculty")	175	976

Note When performing actual searches, use the NEAR/3 operator in Web of Science and the W/3 operator in Scopus.

2.1.3 Inclusion and Exclusion Criteria

To refine the sample and ensure research relevance, strict inclusion (IN) and exclusion (EX) criteria were established in Table 2:

Table 2 Inclusion and exclusion criteria

Inclusion Criteria (IN)	Exclusion Criteria (EX)
IN1:Published between January 1, 2016, and December 31, 2025.	Documents were excluded if they met ANY of the following conditions:
IN2:Published in peer-reviewed research outlets (including journal articles and selected conference papers).	EX1:The research context is non-educational.
IN3:Search terms appear in the document's title, abstract, or keywords.	EX2:The primary subjects of the study are not teachers.
IN4:Language is English.	EX3:The complete full text could not be accessed.
	EX4:The research is not original.

2.1.4 Screening Process

The literature screening followed a systematic, two-stage process (Fig. 1) to ensure transparency and reproducibility:

First-stage Screening: Initial retrieval yielded 4,770 records (787 from WOS, 3,983 from Scopus). Duplicate records (n=568) were removed using EndNote 20 and manual cross-verification, resulting in 4,202 unique records. Two independent researchers screened titles and abstracts against IN1–IN4 and EX1–EX2, excluding 1,541 irrelevant records (e.g., student-focused studies, non-educational contexts). Discrepancies (n=37) were resolved via consensus with a third researcher.

Second-stage Screening: The remaining 2,661 records underwent full-text screening against EX3–EX4. A total of 434 records were excluded (312 with unavailable full texts, 122 non-original research). Finally, 2,227 valid records were retained as the final sample for bibliometric and qualitative analysis.

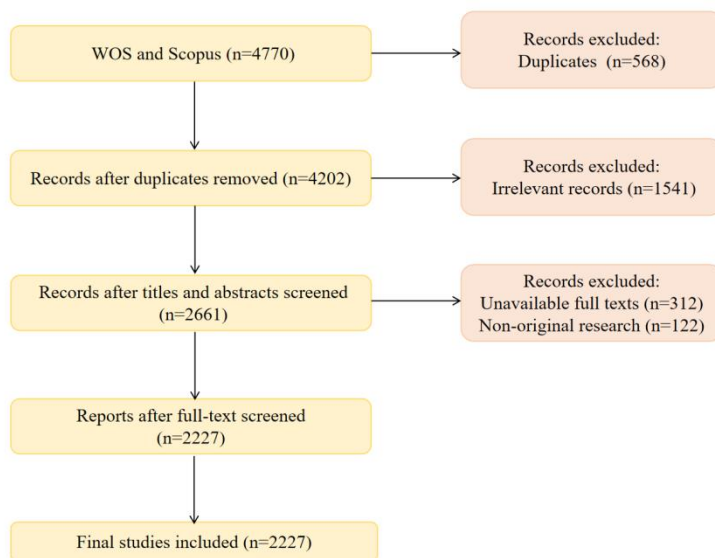


Figure 1 Data collecting and screening process

2.2 Data Analysis

A mixed-methods research approach integrating bibliometric analysis and qualitative thematic synthesis was adopted to address the research questions. This combination facilitates macro-level mapping of the research landscape (via bibliometric analysis) and in-depth interpretation of thematic implications (via qualitative synthesis), thereby enhancing the validity and richness of the research findings.

Bibliometric analysis was performed using CiteSpace 6.4.R1 to identify knowledge structures, thematic clusters, and emerging research trends. Key procedures involved analyzing national and contributor collaboration networks, conducting keyword clustering via the Log-Likelihood Ratio (LLR) algorithm following comprehensive term preprocessing, and detecting burst keywords to trace research frontiers (parameters: $\gamma=1.0$, minimum burst duration=3 years).

To complement and contextualize the bibliometric findings, a qualitative thematic synthesis was conducted on a sample of 120 pivotal publications, selected based on citation frequency, representation in core thematic clusters, and recency. This synthesis adhered to a structured three-step process: coding core concepts, categorizing codes into thematic domains, and integrating these domains with bibliometric clusters. This approach aimed to construct a coherent intellectual framework and validate emerging research directions.

III.RESULTS

3.1. Geographical distribution and collaborative networks

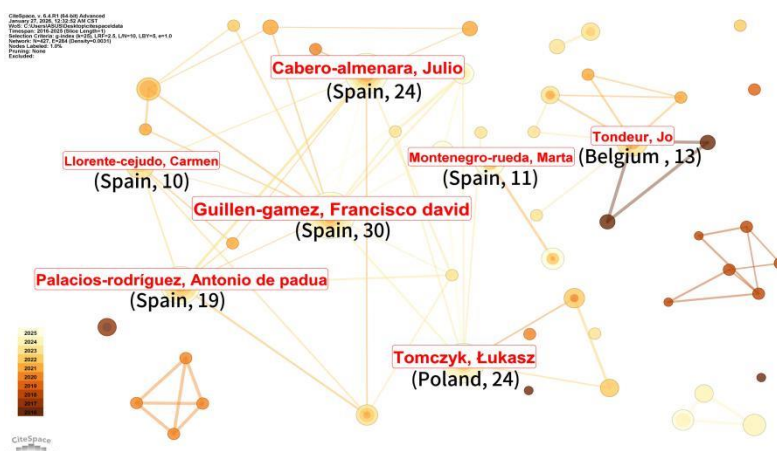


Figure 2 Collaboration network among the most prolific authors (publication count ≥ 10)

Derived from the final sample, the 2,227 valid publications originate from 109 countries and regions, reflecting the global attention that TDC research has garnered. The geographical distribution of TDC research exhibits concentrated output alongside a distinct misalignment between research productivity and collaborative influence.

Spain leads the field with 446 publications, accounting for 20.03% of the total sample, followed by China (318 publications, 14.28%), the United States (157 publications, 7.05%), Indonesia (102 publications, 4.58%), and Norway (92 publications, 4.13%). These five countries collectively contribute 49.07% of the global TDC research output. Crucially, while Spain and China dominate in terms of publication quantity, Australia demonstrates the highest collaboration centrality (0.32) among the top 10 publishing countries. This positions Australia as a pivotal intermediary in the global knowledge network, facilitating cross-regional research partnerships among European, Asian, and American scholar groups. Further analysis of the collaboration network reveals that high-output countries tend to form intra-regional collaborative clusters, with relatively limited inter-regional collaboration intensity.

Core authors in TDC research are predominantly affiliated with institutions in high-output countries, with a notable concentration at Spanish institutions—including top-prolific authors Guillen-Gamez ($n=30$) and Cabero-Almenara ($n=24$), among others. The author co-occurrence network (Fig. 2) indicates that this group forms a dense, internally collaborative cluster, with Guillen-Gamez at its center. Within the context of limited cross-national collaboration, Tomczyk (Poland) is directly connected to the Spanish cluster, while Jo Tondeur (Belgium) forms more independent, regionally focused collaborative hubs.

3.2 Thematic clusters and burst keyword analysis

3.2.1 Core thematic structure

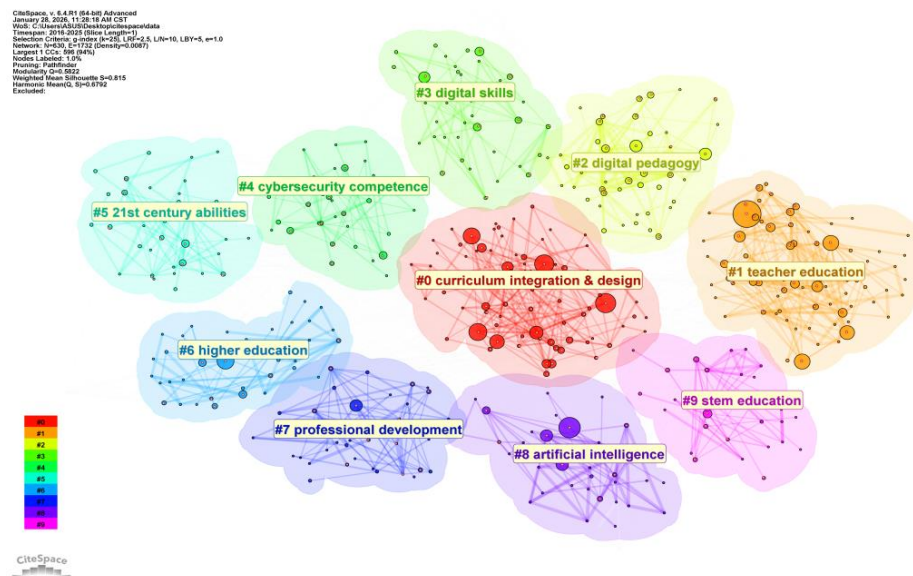


Figure 3 Keyword clustering mapping

Note The figure shows only the top 10 largest clusters (based on node count). Cluster names have been summarized and renamed based on core terms generated by the LLR algorithm.

Keyword clustering was conducted using the Log-Likelihood Ratio (LLR) algorithm, with network pruning via the Pathfinder algorithm. The analysis generated 16 clusters, with a modularity (Q=0.58) exceeding the acceptable threshold of 0.4 and a mean silhouette score (0.815) above the satisfactory threshold of 0.5 [21]. This indicates robust cluster separation and high internal consistency. The top 10 clusters (by node count) are displayed in Fig. 3.

3.2.2 Temporal Dynamics of Research Frontiers

Top 21 Keywords with the Strongest Citation Bursts

Keywords	Year	Strength	Begin	End	2016 - 2025
education	2016	15.29	2016	2018	█
teaching	2016	12.12	2016	2018	█
surveys	2016	11.2	2016	2021	█
information management	2016	2.81	2016	2019	█
information and communication technologies	2016	2.77	2016	2020	█
teaching and learning	2016	2.71	2016	2018	█
pre service teacher education	2016	2.44	2016	2018	█
technology enhanced learning	2017	8.08	2017	2019	█
pre service teacher	2017	5.18	2017	2021	█
educational technology	2016	5.17	2017	2019	█
curricula	2016	4.04	2017	2020	█
content analysis	2017	2.49	2017	2022	█
initial teacher training	2018	4.11	2018	2020	█
digital resources	2018	3.47	2018	2020	█
continuing education	2019	2.61	2019	2022	█
perception	2020	4.49	2020	2022	█
covid-19 pandemic	2021	10.74	2021	2023	█
online education	2021	4.33	2021	2023	█
virtual reality	2021	2.79	2021	2023	█
on line education	2021	2.78	2021	2023	█
distance learning	2022	3.81	2022	2025	█

Figure 4 Top 21 keywords with the strongest citation bursts

Burst keyword analysis identified 21 high-impact burst terms, which revealed four distinct phases in the evolution of research focus from 2016 to 2025 (Fig.4).

The Foundation Phase (2016–2018) was dominated by broad conceptual terms (e.g., “education” and “teaching”) as well as methodological tools (e.g., “surveys” and “content analysis”), with a primary focus on defining TDC and establishing empirical research paradigms. This was followed by the Integration Phase (2017–2020), which was marked by a shift toward practical implementation; burst terms during this period included “technology-enhanced learning”, “digital resources”, and “pre-service teacher education”, emphasizing the integration of TDC into teacher training and curriculum design. The Pandemic-Response Phase (2021–2023) exhibited the strongest burst intensity for “COVID-19 pandemic” (strength=10.74), along with “online education”, “virtual reality”, and “distance learning”—terms that addressed the urgent need for remote teaching competencies amid global educational disruptions. Currently, the Frontier Deepening Phase (2022–2025) is characterized by the most persistent frontier term “distance learning” (duration: 2022–2025), reflecting sustained scholarly inquiry into hybrid teaching models and context-specific TDC application.

IV. DISCUSSION

4.1 Academic landscape

The finding that Spain dominates global publication volume (20.03%) is consistent with prior research [16][22]. However, this study further uncovers the “country-team-individual” synergy that underpins Spain’s leading position in TDC research. At the national level, policies such as the Marco común de competencia digital docente have fostered a supportive research ecosystem conducive to sustained output[23]. At the institutional level, dense collaborative networks among Spanish scholars—such as the research hub led by Guillen-Gamez—have generated the “accumulated advantage” typical of core research clusters: resource sharing and mutual citation enhance scholarly visibility, thereby reinforcing Spain’s dominant status in the field[24].

Notably, Australia’s highest collaboration centrality (0.32), despite its relatively lower publication volume, highlights a critical distinction between “quantity” and “structural influence” in global knowledge networks. This finding identifies Australia as a key intermediary bridging European, Asian, and American research communities. Such an intermediary role underscores the significance of cross-regional collaboration in addressing global digital divides—a gap previously highlighted in the literature but rarely empirically mapped in bibliometric studies on TDC.

Furthermore, the concentration of 49.07% of global publications in five countries (Spain, China, the United States, Indonesia, and Norway) reflects a North-South imbalance in the field. Most TDC research focuses on high-income or upper-middle-income contexts, while resource-constrained regions remain underrepresented. This aligns with Saltos-Rivas et al.’s (2023) observation that TDC research in low-income countries is scarce, emphasizing the need for targeted capacity-building initiatives to ensure the inclusive development of digital education systems worldwide [16].

4.2 Connotation and academic value of the thematic domain

The integration of 16 keyword clusters into five core thematic domains—Competence Dimensions and Frameworks, Teacher Education and Professional Development, Curriculum Integration and Digital Pedagogy, Domain-Specific Adaptation, and Artificial Intelligence Competence—addresses a key limitation of existing research: the fragmentation of studies across isolated themes [22]. This synthesis provides a holistic intellectual structure for the field, clarifying the interdependencies between theoretical construction, practical training, and contextual application of TDC.

1) Competence Dimensions and Frameworks

This domain, which encompasses the “Digital Skills” and “21st Century Abilities” clusters, reflects the field’s evolution from a skill-centered to a holistic conceptualization of TDC. The dominance of the DigCompEdu framework in the core terms of these clusters (e.g., “professional digital competence”, “digital resource utilization”) confirms its status as a global benchmark for TDC [19][20]. However, the clustering results of this

study also highlight emerging critiques: existing frameworks often lack alignment with teachers' professional development needs [25] and fail to incorporate emerging literacies (e.g., algorithmic governance [26]).

The three identified trajectories of assessment tool development—localized validation, independent model construction, and automated evaluation—address the longstanding issue of social desirability bias in self-reported TDC data [7]. For instance, de-Torres et al.'s (2024) LMS-based automated assessment, highlighted in the "Digital Skills" cluster, offers a scalable, objective alternative to traditional questionnaires, filling a methodological gap in large-scale TDC evaluation [8].

2) Teacher education and professional development

The clustering of "Teacher Education" and "Professional Development" underscores the continuum of TDC cultivation across pre-service and in-service stages. Pre-service TDC research emphasizes foundational digital pedagogy training (e.g., digital storytelling [27]) and the mediating role of epistemological beliefs [28]. In contrast, in-service studies focus on context-adapted training models (e.g., blended learning [9]) and multi-level influencing factors (e.g., school support, professional identity [29]).

A core insight of this domain—differentiated training strategies for diverse teacher groups (e.g., by age, gender, or discipline)—addresses the field's call for personalized TDC development [30]. The dense semantic links between this domain and "Curriculum Integration and Digital Pedagogy" further confirm that effective TDC training must be anchored in authentic pedagogical practice, rather than isolated technical skill acquisition.

3) Curriculum integration and digital pedagogy

As the central hub connecting other thematic domains, this cluster—encompassing "Curriculum Integration & Design" and "Digital Pedagogy"—highlights the core essence of TDC: translating digital competence into effective teaching practice. The prominence of the TPACK model in the cluster's core terms reinforces its role as the theoretical foundation for digital pedagogy [31]. Derivative models such as MPC (Media-Pedagogy-Content [32]) further demonstrate the field's shift toward context-specific theoretical adaptation.

The cluster's high silhouette score (0.918 for "Digital Pedagogy") indicates strong scholarly consensus on its core components: inclusive education, technology-integrated curriculum design, and instrument validation. This consensus addresses prior criticisms of vague digital pedagogy definitions [33], providing a clear framework for practical application and assessment in educational settings.

4) Domain-specific adaptation

The clustering of "Cybersecurity Competence", "Higher Education", and "STEM Education" reflects the field's growing recognition that TDC is not a one-size-fits-all construct. STEM education research, in particular, emphasizes unique requirements such as cross-boundary collaboration and the integration of emerging technologies (e.g., VR/AR [10]), distinguishing it from general TDC frameworks.

The multidimensional structure of TDC in higher education—encompassing digital literacy, skills, interaction, and integration [11]—highlights the complexity of digital competence in post-secondary contexts, where teachers must balance research, teaching, and student mentorship. The emergence of cybersecurity competence as a standalone cluster signals a critical shift: digital ethics and data protection are no longer peripheral but foundational components of TDC [34][35], addressing gaps in earlier frameworks.

5) Artificial Intelligence Competence

The distinctness of the "Artificial Intelligence" cluster confirms AI competence as a transformative dimension of TDC. The core contribution of this domain lies in distinguishing AI competence from general digital competence—highlighting unique requirements such as ethical AI use, algorithmic literacy, and adaptive teaching with AI tools [36].

The integration of AI into TDC requires both technical training and pedagogical reorientation. This dual necessity arises because mastering AI tools does not automatically translate into their effective and critical use in educational contexts. Factors such as psychological safety [37] and institutional infrastructure [38] further emphasize that AI competence development is a socio-technical process, rather than merely the acquisition of technical skills.

4.3 Evolutionary logic of research frontiers

Burst keyword analysis demonstrates that the research focus of this field has evolved sequentially from “conceptual foundation” (2016–2018) to “technology integration” (2017–2020), “pandemic response”(2021–2023), and ultimately to “frontier deepening” (2022–2025). Particularly notably, the persistence of “distance learning” as the core frontier in the current period (2022–2025) signifies the practical validation of the “Curriculum Integration and Digital Pedagogy” domain under extreme contextual pressures.

The pandemic served as a global “stress test” for Technology-Enhanced Digital Curriculum (TDC), exposing not only gaps in technological access [39] but also shortcomings in context-specific digital pedagogy [40]. This paradigm shift—from questioning “whether TDC matters” to exploring “how to apply TDC in specific contexts”—aligns with Falloon’s (2020) TDC framework, which emphasizes dynamic adaptation to complex digital environments [6]. The integration of “distance learning” with other burst keywords (e.g., “virtual reality”, “online education”) further indicates that post-pandemic TDC research centers on hybrid teaching models—combining in-person and remote instruction—rather than temporary emergency measures.

V. CONCLUSION

This study systematically maps the evolutionary landscape of Teacher Digital Competence (TDC) research over the decade 2016–2025 through a mixed-methods approach that integrates bibliometric analysis and qualitative synthesis, generating comprehensive insights into the field’s scholarly architecture, core themes, and emerging frontiers. A bibliometric analysis of 2,227 publications validates the field’s robust growth trajectory: Spain emerges as the top contributor in terms of publication output, while Australia plays a pivotal intermediary role in global international collaboration networks. Beyond quantifying the field’s expansion, the core contribution of this study lies in synthesizing the fragmented intellectual terrain of TDC research into five interrelated thematic clusters: Competence Dimensions and Frameworks, Teacher Education and Professional Development, Curriculum Integration and Digital Pedagogy, Domain-Specific Adaptation, and Artificial Intelligence Competence. These clusters underscore TDC as a dynamic, multidimensional construct intertwined with pedagogical innovation, institutional backing, and technological progress. Furthermore, burst keyword analysis identifies “distance learning” as a critical and enduring research frontier, highlighting the profound impact of the COVID-19 pandemic on redirecting research priorities toward practical competencies for remote and hybrid teaching contexts.

Despite these contributions, the study is not without limitations. First, the reliance on Web of Science and Scopus as primary data sources may have excluded relevant literature from regional databases and non-English publications, potentially leading to the underrepresentation of TDC research in resource-constrained contexts and non-Western educational systems. Second, while bibliometric analysis effectively captures macro-level trends and thematic clusters, it lacks in-depth scrutiny of the methodological rigor and theoretical depth of individual studies—an oversight that could be addressed by incorporating qualitative case study approaches. Third, the concentration of research in high-income and upper-middle-income countries underscores a regional imbalance: limited attention has been paid to the unique challenges and needs of TDC development in low-resource settings, and cross-cultural comparative studies remain scarce.

Moving forward, expanding literature searches to encompass multilingual and regional publications would yield a more inclusive evidence base. Complementing bibliometric analysis with qualitative inquiry could generate richer insights into how digital competence is enacted in real-world educational contexts. There is also a clear need to direct research efforts toward understudied settings and emerging demands—such as those related to distance education and artificial intelligence (AI)—to support the development of context-responsive and forward-looking TDC frameworks.

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