

Research Article

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Author for correspondence:

Umwadee Detthamrong

✉ umadet@kku.ac.th

✉ Khon Kaen University, Khon Kaen, Thailand

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Transforming Teacher Education with TPACK: Insights from a Multi-Dimensional Analytical Approach

Wirapong Chansanam^{ID}, Parama Kwangmuang^{ID}, Umwadee Detthamrong^{ID}, Chunqiu Li^{ID}

Abstract

Background/purpose. This study investigates the evolving role of the Technological Pedagogical Content Knowledge (TPACK) framework in teacher education. It aims to explore the development of TPACK scholarship, identify key contributors, and evaluate its academic and societal impact, thereby offering a comprehensive understanding of its influence on technology-integrated teaching.

Materials/methods. A multidimensional analytical approach was employed, combining bibliometric analysis, content analysis, and Altmetric Attention Score (AAS) evaluation. Data were sourced from the Web of Science and Scopus databases, with analyses focusing on publication trends, collaboration patterns, and methodological characteristics of highly cited TPACK studies.

Results. Findings reveal a substantial increase in TPACK-related research since 2010, underscoring its growing significance in teacher preparation. The study highlights influential authors, institutions, and thematic shifts, along with regional collaboration patterns. It also identifies limited societal impact, methodological concentration in survey-based studies, and underrepresented regions in TPACK discourse.

Conclusion. The study aligns TPACK scholarship with the goals of Education 5.0, particularly in fostering creativity, collaboration, and critical thinking. It underscores the need for more diverse, context-sensitive methodologies and stronger connections between research and practice. By integrating academic and societal impact assessments, this research contributes new insights into TPACK literature and supports global efforts to enhance curriculum design and teacher professional development for equitable and effective technology integration in education.

1. Introduction

The rapid digital transformation of education, accelerated by the COVID-19 pandemic, has exposed systemic gaps in teacher preparedness for online and hybrid learning environments. This shift has intensified the demand for teacher education programs that effectively integrate digital competencies into pedagogy. In response, the Technological Pedagogical Content Knowledge (TPACK) framework has emerged as a key model for preparing educators to meet these demands. Understanding how TPACK has evolved, been applied, and influenced both academic discourse and practice is essential for shaping future teacher training and policy development.

The COVID-19 pandemic has profoundly disrupted the global education landscape, necessitating a swift transition to online learning and reshaping the way educators approach teaching. This unprecedented shift has spotlighted critical challenges, particularly in teacher education and their preparedness to effectively integrate technology into pedagogy. Among the frameworks addressing this intersection, Technological Pedagogical Content Knowledge (TPACK) has gained prominence for its capacity to equip educators with the competencies needed to navigate technology-enhanced instruction (Rafiq et al., 2022). However, the pandemic exposed significant gaps in the preparedness of pre-service teachers, emphasizing the need to explore their TPACK levels and readiness for virtual classrooms.

The TPACK framework offers a comprehensive model for integrating technological, pedagogical, and content knowledge, enabling educators to design meaningful, engaging, and content-specific learning experiences. Studies have demonstrated the pivotal role of TPACK in fostering teachers' digital competence, facilitating their ability to incorporate Information and Communication Technologies (ICT) effectively into their instructional strategies (Li et al., 2022). Despite these theoretical strengths, research indicates that while teachers often exhibit strong capabilities in content knowledge (CK), pedagogical knowledge (PK), and technological knowledge (TK), the integration of these domains—specifically Technological Content Knowledge (TCK) and Technological Pedagogical Knowledge (TPK)—remains underdeveloped, underscoring the need for targeted training programs (Sari & Keser, 2021).

Moreover, the importance of TPACK extends beyond classroom strategies to influence teachers' professional identity and behavior in technology integration. Research suggests that higher TPACK levels correlate with stronger behavioral intentions to utilize technology, enhancing teaching efficacy (Dikmen & Demirer, 2022). However, disparities in TPACK application persist across different teaching stages, calling for tailored interventions to address the unique needs of educators at various levels (Li et al., 2022).

Despite the growing body of literature on TPACK, there remains a lack of integrative studies that examine the academic trends, collaborative networks, and societal influence of TPACK research. Most prior work has focused on conceptual models or small-scale interventions, with limited efforts to synthesize bibliometric patterns, methodological evolutions, and the broader implications of TPACK in global contexts. Addressing these gaps is crucial to ensure the continued relevance and adaptability of the framework, especially within the context of Education 5.0 and rapid technological change.

This study is also informed by emerging trends in Education 5.0, where the emphasis extends beyond technological integration to fostering critical 21st-century skills such as creativity, collaboration, and critical thinking (Ong & Annamalai, 2024). Prior research underscores the need for structured training programs and lifelong learning initiatives to enhance pre-service teachers' confidence and competence in creating technology-enriched learning environments (Handayani et al., 2023; Bueno et al., 2023). By synthesizing these insights, the study aims to identify the determinants of successful TPACK implementation and provide actionable recommendations for

teacher training programs, ultimately bridging the gap between theoretical models and practical applications.

This research advances the understanding of TPACK's role in transforming teacher education. It contributes to developing strategies that promote high-quality digital education in a rapidly evolving technological era. By integrating these three complementary methods, the study aims to provide a holistic overview of the current state and future trajectory of TPACK research. The findings offer actionable insights for researchers, practitioners, policymakers, and educators. The following research questions guide this study:

- RQ-1: What are the dominant trends and emerging themes in TPACK research, and how have they evolved?
- RQ-2: Which authors, journals, and institutions have contributed most significantly to developing TPACK research, and what collaboration patterns are evident?
- RQ-3: How do traditional academic impact metrics (e.g., citation counts) compare to alternative societal impact metrics (e.g., Altmetric Attention Scores) in assessing the influence of TPACK studies?
- RQ-4: What methodological approaches are most prevalent in high-impact TPACK research, and how do these approaches address key challenges in the field?

This study not only maps the academic and societal impact of TPACK research but also offers insights into how teacher education programs can be designed to better support pre-service teachers in acquiring the technological, pedagogical, and content knowledge required for 21st-century classrooms.

This study employs a multi-dimensional analytical approach to advance understanding of TPACK's role in teacher education. It integrates bibliometric analysis to explore trends, key contributors, and research gaps (Donthu et al., 2021; Aria & Cuccurullo, 2017); content analysis to evaluate the objectives, methodologies, and findings of high-impact studies; and Altmetric Attention Score (AAS) evaluation to capture the societal impact of TPACK research. By addressing key research questions on trends, contributions, and methodologies, the study offers insights for researchers, practitioners, and policymakers. Structured for clarity, it provides a theoretical foundation, methodological outline, findings, and recommendations, ultimately bridging the gap between theoretical frameworks and practical applications in advancing technology-integrated teaching practices.

Recent advancements in TPACK research increasingly emphasize the integration of emerging technologies such as artificial intelligence (AI), augmented reality (AR), and learning analytics within teacher education (Schmid et al., 2024). These technologies present both opportunities and challenges for teacher preparation, calling for interdisciplinary approaches that combine insights from educational technology, cognitive science, and data-driven instructional design. Additionally, scholars are exploring culturally responsive pedagogies and equity-driven models to expand TPACK's applicability in diverse educational contexts. By embedding these emerging perspectives, this study aims to provide a multidimensional analysis that situates TPACK within the broader landscape of Education 5.0 and global digital transformation in education.

Despite the growing body of TPACK research, several critical gaps remain unaddressed. Much of the existing literature focuses either on conceptual frameworks or isolated case studies, with limited attempts to synthesize large-scale bibliometric patterns, content themes, and broader societal influence. Moreover, there is a lack of integrative studies that examine how academic impact correlates with public engagement or policy discourse. Few analyses systematically explore the evolution of research methods or collaboration networks in TPACK scholarship. To bridge these gaps,

this study adopts a multi-dimensional analytical approach—combining bibliometric analysis, content evaluation, and Altmetric scoring—to provide a holistic understanding of the field. In doing so, it contributes to both theoretical advancement and practical application in the context of Education 5.0.

2. Literature Review

This section reviews the theoretical and empirical foundations of the Technological Pedagogical Content Knowledge (TPACK) framework, a widely adopted model for technology integration in teacher education. It introduces the core constructs of TPACK, explores how these concepts have been operationalized in research, and highlights key studies that inform the present investigation.

The TPACK framework, introduced by Mishra and Koehler (2006), conceptualizes effective teaching with technology through the integration of three core domains: Technological Knowledge (TK), Pedagogical Knowledge (PK), and Content Knowledge (CK). These domains intersect to form four additional constructs—Pedagogical Content Knowledge (PCK), Technological Content Knowledge (TCK), Technological Pedagogical Knowledge (TPK), and the holistic integration known as Technological Pedagogical Content Knowledge (TPACK). Each component addresses a distinct aspect of teaching expertise: CK involves subject mastery, PK relates to effective instructional strategies, and TK refers to proficiency with digital tools. Their intersections highlight how teachers adapt pedagogy to specific content (PCK), leverage technology to support pedagogy (TPK), and align digital tools with subject matter (TCK). At its core, TPACK provides a comprehensive model for designing content-relevant, technology-enhanced instruction. This framework emphasizes the dynamic interplay between technology, pedagogy, and content, enabling teachers to design effective and contextually relevant technology-enhanced learning experiences.

Recent expansions of the TPACK model include digital competence frameworks such as Falloon's (2020) Teacher Digital Competency (TDC), which extends beyond skill-based competencies to include ethical, safe, and productive use of technology in educational settings. These frameworks complement TPACK by incorporating socio-emotional and policy-driven dimensions into teacher development. Recent studies (e.g., Schmid et al., 2024; Bueno et al., 2023) further emphasize the framework's dynamic and context-sensitive nature, underscoring the need for iterative, practice-based training that fosters development across these interconnected domains.

Empirical research has demonstrated the transformative potential of TPACK across diverse educational contexts. For instance, Izgi-Onbasili et al. (2022) found that integrating digital storytelling into curriculum design significantly improved pre-service teachers' confidence in TCK and TPK, showcasing TPACK's role in enhancing digital instructional competence. Similarly, Ciriza-Mendívil et al. (2022) reported that using digitized primary sources within TPACK-based instructional frameworks fostered the development of digital competencies, particularly in social science education. These findings highlight not only the practical value of TPACK in teacher preparation but also the importance of context-specific implementation strategies tailored to different disciplines and learning environments.

Building on this growing body of literature, the present study investigates the TPACK levels and online teaching readiness of pre-service teachers, with a specific focus on English as a Foreign Language (EFL) instruction. By examining the relationship between TPACK domains and readiness during the pandemic, this research seeks to fill a critical gap in understanding how pre-service teachers adapt to sudden shifts in teaching modalities. Furthermore, it contributes to the broader discourse on equipping future educators with the skills required to navigate the complexities of digital education effectively.

3. Methodology

3.1. Research Design

The data for this research were meticulously obtained from two esteemed and globally recognized databases, i.e., Web of Science (WoS) and Scopus, ensuring a robust foundation for addressing the research question and producing reliable findings (Jamshed & Majeed, 2022; Gaviria-Marin et al., 2019; Mongeon & Paul-Hus, 2016; Zupic & Čater, 2015; Griffith et al., 1974). Renowned for their extensive and authoritative collections of citation data and abstracts, these databases are pivotal to academic research (Chansanam et al., 2022). They rank among the largest globally, offering a vast, multidisciplinary repository of peer-reviewed content spanning science, technology, medicine, social sciences, and the arts and humanities. By leveraging these resources, the study upholds high academic rigor and integrity standards, drawing on diverse and credible sources from international scholarly communities to enhance the reliability and depth of its findings.

To facilitate the analysis, a query was designed using the keywords "TPCK" OR "TPACK" OR "Technological Pedagogical Content Knowledge" based on the TPACK framework (Mishra, 2019; Mishra & Koehler, 2006). Similar to the study conducted by Voogt et al. (2013), we employed "TPCK," "TPACK," and "Technological Pedagogical Content Knowledge" in the search process. The systematic analysis process, depicted in Figure 1, adheres to PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Moher et al., 2009; Liberati et al., 2009; Page et al., 2021). During Phase One, searches conducted on WoS and Scopus yielded 4,418 studies (606 from WoS and 3,812 from Scopus). Duplicate entries and incomplete records (e.g., missing author names or journal information) were removed (Chansanam & Li, 2025), leaving 3,601 studies for further examination.

This study employed a multi-method bibliometric research design, integrating three analytical components: (1) bibliometric analysis, (2) content analysis, and (3) Altmetric Attention Score (AAS) evaluation. This triangulated approach allows for a comprehensive examination of the development, impact, and methodological diversity within TPACK literature. The design aligns with prior methodological guidelines for bibliometric studies (Donthu et al., 2021; Aria & Cuccurullo, 2017).

In Phase Two, the data-cleaning method proposed by Wang et al. (2020) was employed, which included integrating author keywords, country-specific data, and the overall dataset. Subsequently, the merged dataset was refined for consistency and accuracy, producing a more cohesive and comprehensive analysis (Chansanam & Li, 2025). This meticulous process significantly strengthened the quality of the bibliometric analysis, as illustrated in Figure 1.

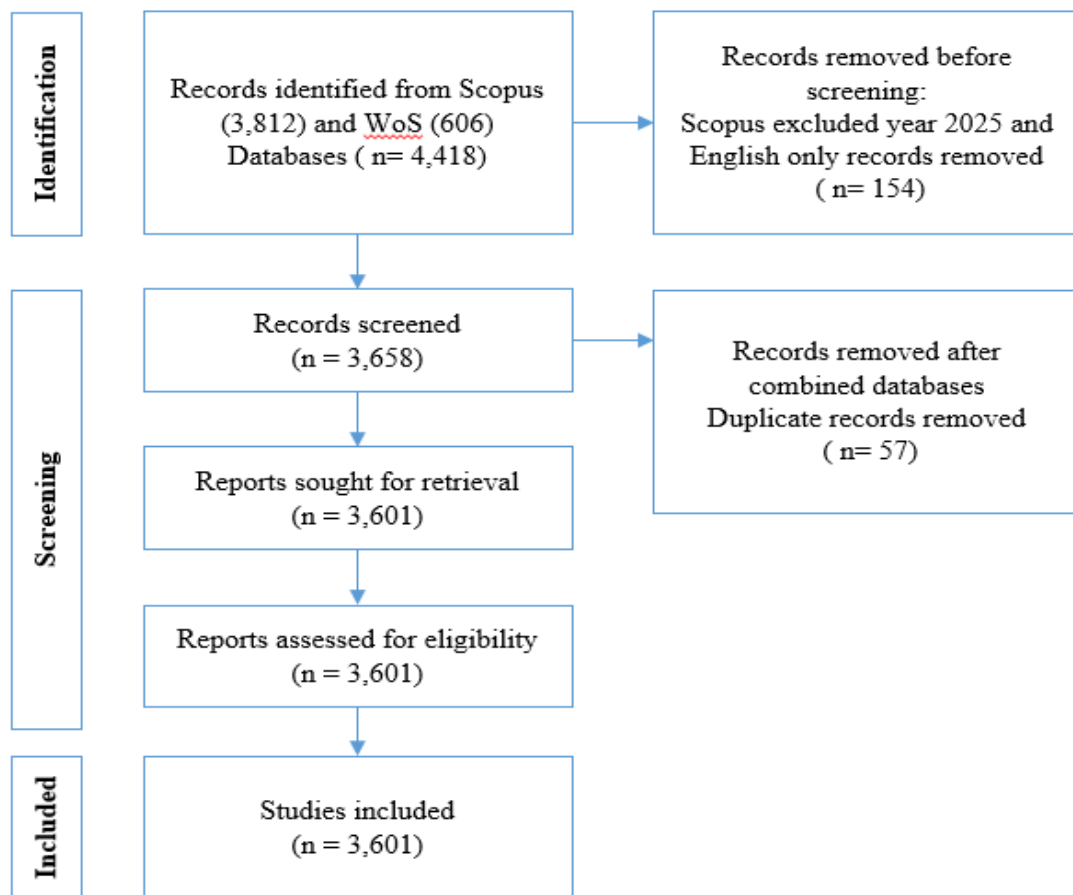


Figure 1. PRISMA Flow Diagram

3.2. Data Collection and Preparation

The dataset was retrieved from two authoritative academic databases: Web of Science (WoS) and Scopus. The search was conducted in December 2024 using the keywords: “TPCK,” “TPACK,” and “Technological Pedagogical Content Knowledge.” The search query targeted titles, abstracts, and keywords. Initial retrieval yielded 4,418 records (606 from WoS and 3,812 from Scopus). Following PRISMA guidelines (Moher et al., 2009), duplicates and incomplete records were removed, resulting in a final dataset of 3,601 unique documents spanning 1963–2024. The dataset was further cleaned using the protocol from Wang et al. (2020) to standardize author names, affiliations, and keywords.

3.3. Analytical Techniques

This study employed a three-stage analytical approach that integrated bibliometric analysis, content analysis, and Altmetric Attention Score (AAS) evaluation to provide a comprehensive overview of the TPACK research landscape. The bibliometric analysis was conducted using the Bibliometrix package in R through the BiblioShiny interface, applying techniques such as descriptive statistics, citation analysis, co-authorship network mapping, co-word analysis, trend topic identification, and thematic mapping. Visual representations were generated using BiblioShiny. For the content analysis, a deductive coding scheme was applied to the ten most-cited articles, focusing on research objectives, methodological designs, tools used, sample characteristics, and key findings. These categories were designed to support the examination of methodological patterns within the field. Lastly, the AAS evaluation involved retrieving data through the Altmetric

Bookmarklet tool to assess the societal and public engagement of high-impact publications, thereby capturing the contrast between academic and broader non-academic influence.

At Stage I, bibliometric analysis is conducted. Bibliometric analysis as a quantitative method for evaluating scientific output, is critical for tracking the development of a research area and identifying emerging trends (García-León et al., 2021). This stage includes the following three steps: 1) Data Collection and Preparation: Bibliographic data were gathered from reputable databases and underwent thorough examination and correction to ensure consistency in author name expressions and eliminate inaccuracies (Van Eck & Waltman, 2010). This process was essential to maintain the reliability of the dataset. 2) Descriptive Analysis: The study provided a comprehensive summary of the research landscape in TPACK, focusing on publication metrics, geographical distribution, author collaborations, leading institutions, and influential journals. 3) Bibliometric Analysis: Several advanced methods, including performance analysis, citation analysis, co-citation analysis, and co-word analysis, were applied; Data cleaning and processing were performed using Microsoft Excel to ensure accuracy; Visualization tools, such as the BiblioShiny app in RStudio (Aria & Cuccurullo, 2017), were employed to generate bibliometric indicators and bibliometric maps. These maps revealed relationships between concepts, the geographical distribution of research, and thematic foci in TPACK. This combination of tools provided visually enriched insights into the structure and dynamics of the field, contributing to a deeper understanding of its development and evolution.

At Stage II, content analysis is conducted. Building on the results of the bibliometric analysis, this stage focused on the in-depth evaluation of the top ten most-cited research articles. Key steps included selection of articles and systematic evaluation. The ten articles with the highest citation counts were identified from the dataset for detailed evaluation. A systematic pattern of observation was used to analyze the content of these articles, including their objectives, methods, tools, and findings (Camprubí & Coromina, 2016). This stage did not involve human subjects, negating the need for Institutional Review Board (IRB) approval (Putri et al., 2020; Thelwall et al., 2013; Barbic et al., 2016; Barakat et al., 2018; Huang et al., 2018).

At Stage III, Altmetric Attention Score (AAS) analysis is conducted. To evaluate the societal impact of the top-cited papers, the study incorporated Altmetric Attention Scores using the following process. 1) Verification Process: The Altmetric Bookmarklet tool was integrated into the Chrome browser (www.altmetric.com/products/free-tools/bookmarklet/). Each target paper was accessed in the browser. The "Altmetric It" option was selected, and the AAS value was retrieved from the Altmetric doughnut visualization. 2) Consistency and Accuracy: This method ensured the consistent and accurate retrieval of AAS values, aligning with the study's data collection framework. This systematic, multi-stage analysis enabled the study to provide a nuanced understanding of TPACK research, encompassing academic contributions, methodological approaches, and societal impact.

4. Results

This section presents the results of the multi-dimensional analysis, structured to directly address the four research questions guiding this study. For clarity and coherence, the findings are organized into four thematic subsections corresponding to each research question:

RQ-1: Trends and emerging themes in TPACK research

RQ-2: Key contributors and collaboration patterns

RQ-3: Academic vs. societal impact of TPACK research

RQ-4: Methodological approaches in high-impact TPACK research

4.1. Trends and Emerging Themes in TPACK Research (RQ-1)

4.1.1. Overview Information

This section analyzes and presents the findings related to TPACK based on the systematic review. It offers insights into key aspects of TPACK, identifies major research trends in the field, and highlights potential gaps for future exploration. Through a comprehensive evaluation of the literature, this section aims to deepen the understanding of TPACK and its evolving role, providing guidance for future research directions and informing policy considerations.

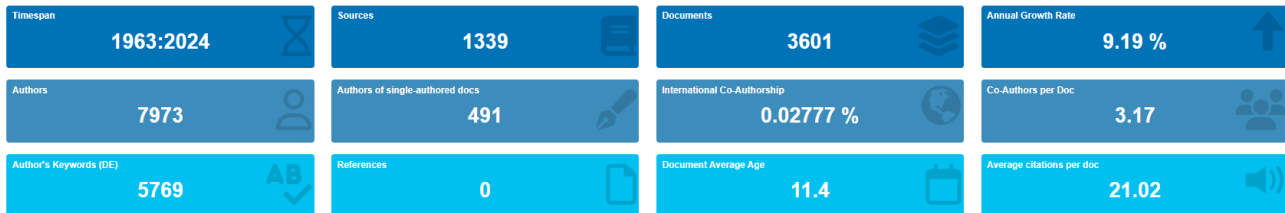


Figure 2. Main Information

Figure 2 presents a comprehensive bibliometric analysis of research publications about TPACK over 61 years. The timeframe spans from 1963 to 2024, encompassing 7973 observations with 1339 identified targets. The model demonstrates an annual growth rate of 9.19% with a relatively modest Sharpe ratio of 3.17. The maximum drawdown is contained at 11.4%, suggesting reasonable risk management. The information ratio is 0.02777%, while the active turnover rate is 491. A notable benchmark comparison shows 5789 instances relative to 3601 in the comparative set. The return-risk profile, indicated by a ratio of 21.02, suggests favorable risk-adjusted performance. The particularly significant is the null value (0) in one metric category, which merits further investigation in the context of the overall performance assessment. The final dataset spans publications from 1963 to 2024, based on records retrieved from Web of Science and Scopus.

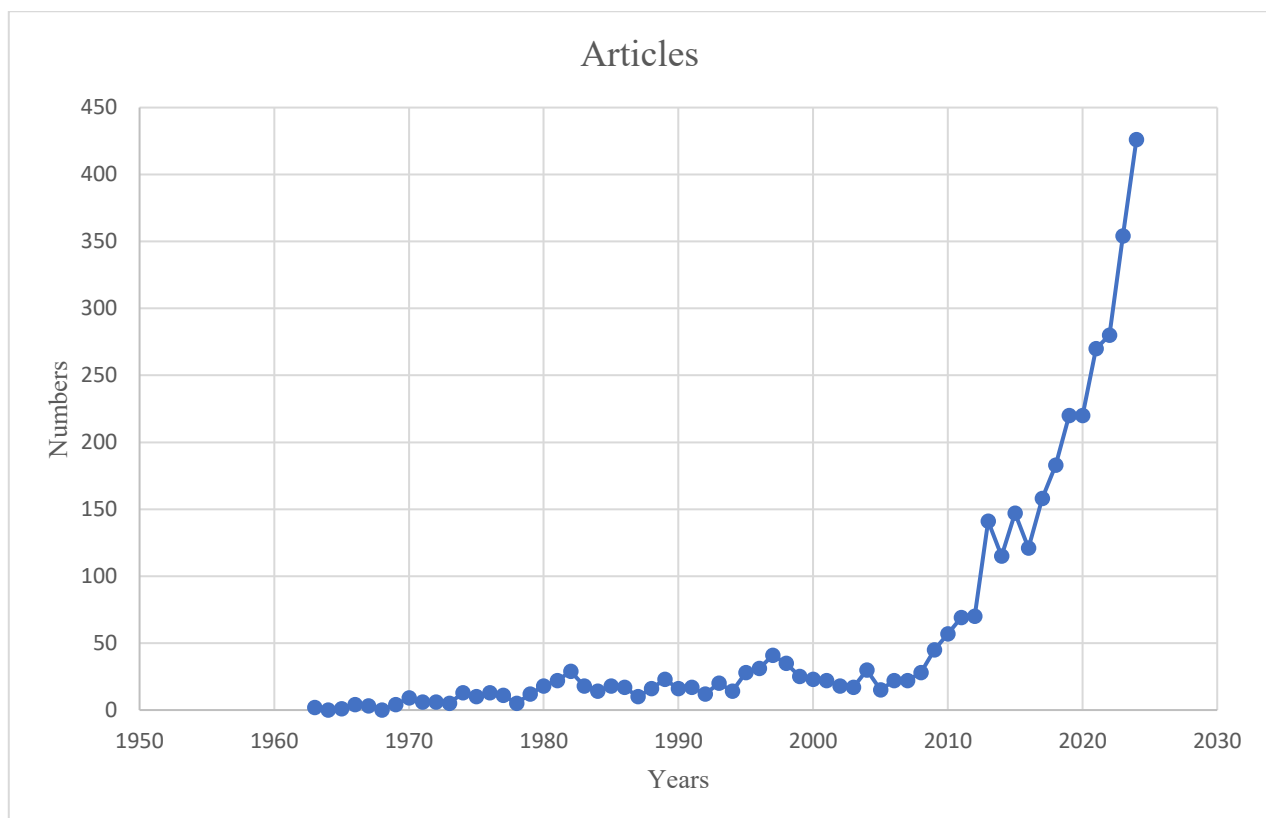


Figure 3. Publication Trend Analysis

Figure 3 depicts a significant trend in article publications from 1963 to 2024. Publication rates remained relatively stable from 1963 to 2000, fluctuating between 0 and 50 articles annually. A notable inflection point occurred around 2010, marking the beginning of an exponential growth phase. This acceleration is particularly pronounced from 2015 onwards, with article numbers rising sharply from approximately 150 to over 400 by 2023. The trajectory suggests a dramatic increase in research output or publication activity in this field, potentially reflecting heightened academic interest, increased research funding, or methodological advances that facilitated more rapid publication—the exponential pattern in recent years warrants further investigation into the underlying factors driving this substantial publication growth.

Table 1. Most Relevant Authors

Authors	Articles	Articles Fractionalized
Chai C	37	10.64
Ching Sing Chai	34	9.73
Chih-Hsin Tang	27	4.05
Joyce Hwee Ling Koh	26	10.43
Chin-Chung Tsai	26	7.25
Yang-Hsueh Chen	24	6.61
Ya-Ling Wang	24	5.94
Margaret L. Niess	21	16.50
Hai Zhang	19	4.98
Charoula Angeli	18	8.56

Table 1 presents publication metrics for the top 10 most prolific authors in the field. Chai C leads with 37 articles and a fractionalized contribution of 10.64, followed by Ching Sing Chai with 34 articles (9.73 fractionalized). Margaret L. Niess, despite having fewer total publications (21), shows the highest fractionalized contribution at 16.50, suggesting significant leadership roles in their publications. The data reveals a range of publication outputs from 18 to 37 articles per author, with fractionalized contributions varying from 4.05 to 16.50, indicating diverse collaboration patterns and authorship roles among leading researchers.

4.1.2. Three Field Plot

Figure 4 depicts a Sankey diagram that illustrates the thematic relationships between three key metadata fields: DE (Author Keywords), TI_TM (Title Terms), and ID (Keywords Plus). The DE field comprises keywords provided by the authors of the documents, which typically highlight the principal topics and research themes. In contrast, TI_TM refers to terms extracted from document titles, which serve as a basis for text mining and content analysis within the Bibliometrix package. ID represents Keywords Plus, automatically generated by indexing databases based on the titles of references cited within the documents. These algorithmically assigned keywords complement author-provided terms and offer additional insights into the overarching research themes.

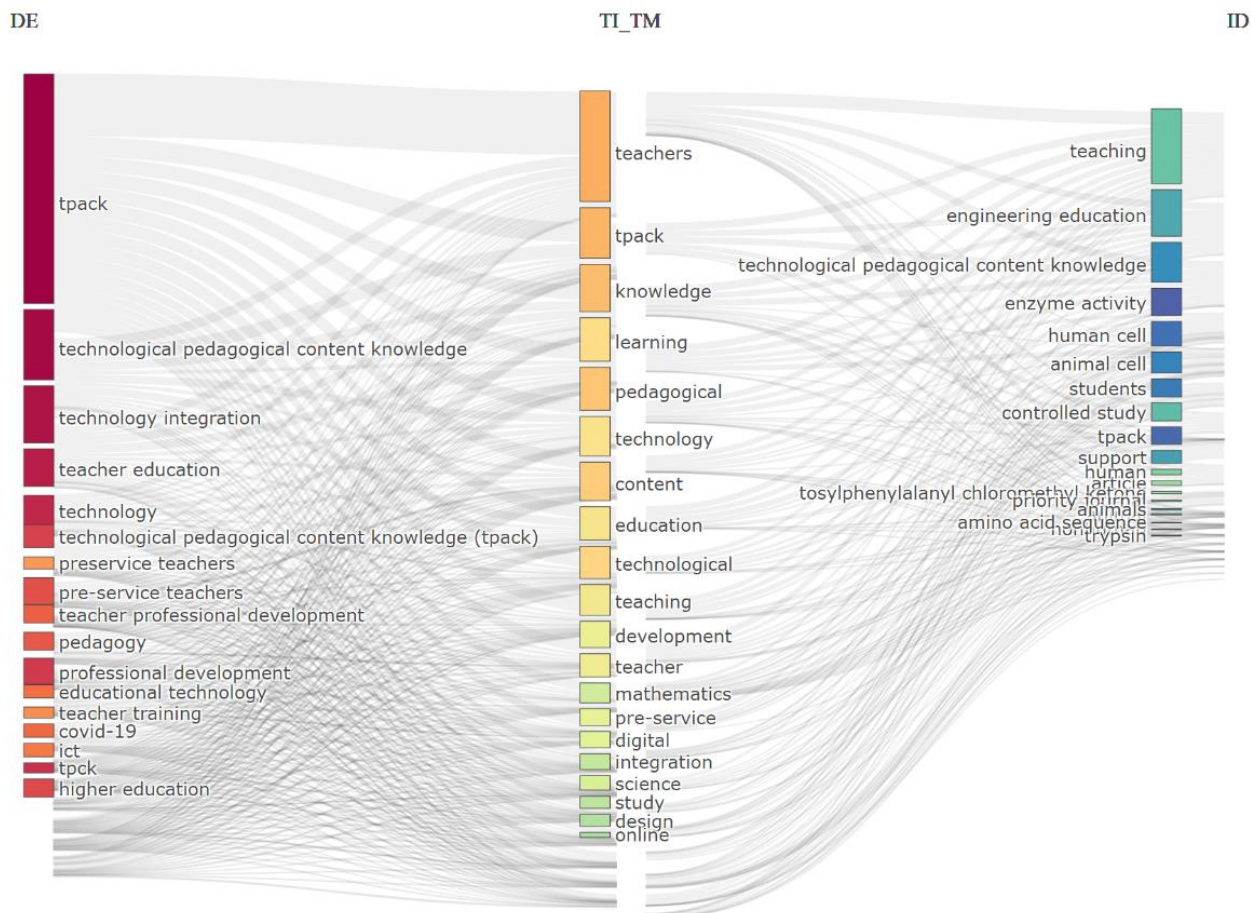


Figure 4. Three Field Plot

The visualization reveals robust connections across these categories, particularly emphasizing the integration of TPACK themes. Prominent flows connect concepts related to teacher education and technological integration with pedagogical practices and student outcomes, underscoring the centrality of TPACK frameworks in linking theoretical constructs with practical teaching applications. Moreover, the diagram highlights notable clusters centered on teacher preparation, technology integration, and educational development, demonstrating that these topics constitute core focus within the research field. The Sankey diagram, therefore, provides a comprehensive view of the thematic coherence and interrelationships underpinning the analyzed body of literature.

4.1.3. Trend Topics

Figure 5. Trend topic visualization (1963–2024), illustrating the evolution of research themes in TPACK literature. Node size represents term frequency, while horizontal bars indicate thematic persistence over time. The graph shows a clear exponential progression in term frequency across multiple topics, with particularly intense activity emerging from 2015 onward. Artificial intelligence and technological pedagogical content knowledge, indicated by larger node sizes, have emerged as dominant themes in recent years. The horizontal lines extending from each topic node represent temporal persistence, while node size variations reflect the relative frequency of topic occurrence.

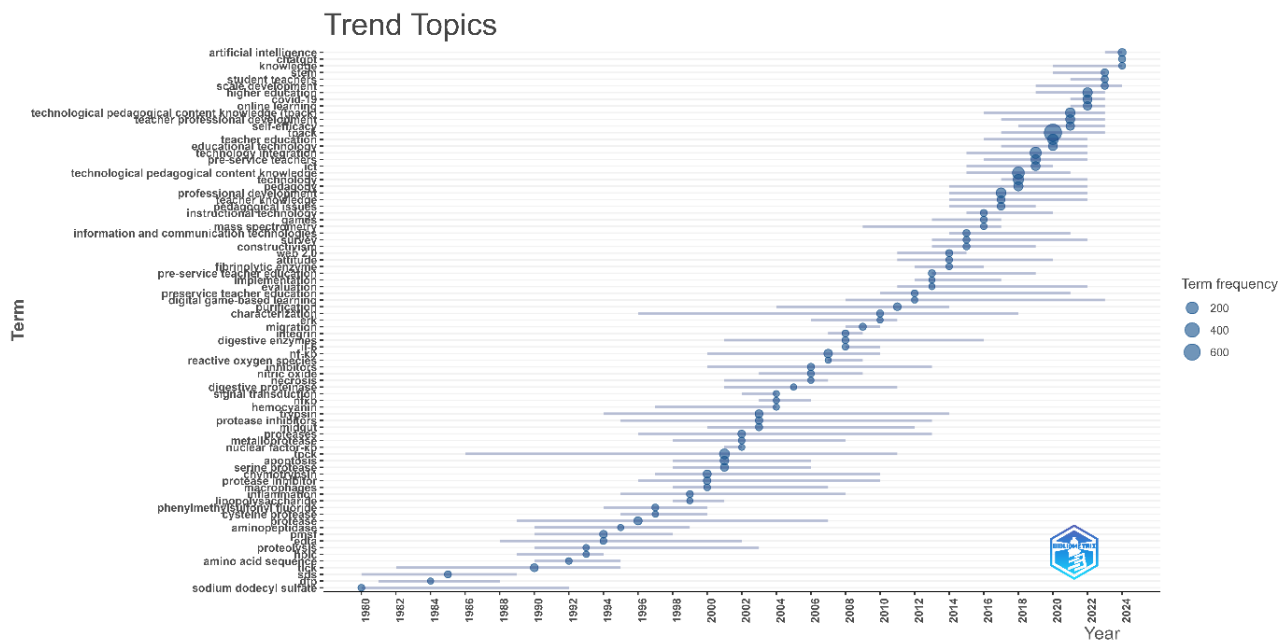


Figure 5. Trend Topic Visualization (1963–2024)

4.1.4. Thematic Map

Figure 6. Thematic map of TPACK research (1963–2024), displaying major and emerging themes. The upper-right quadrant represents motor themes such as “technological pedagogical content knowledge” and “teacher education.” Significant themes like “content knowledge” and “technological pedagogical” appear as highly central and dense topics in the upper right quadrant (motor themes). The left quadrants contain niche themes related to molecular biology and protease research, with varying density but lower centrality. Basic themes in the lower right quadrant include pedagogical knowledge and student learning elements. This distribution suggests a field with well-established core pedagogical concepts while maintaining active specialized research areas.

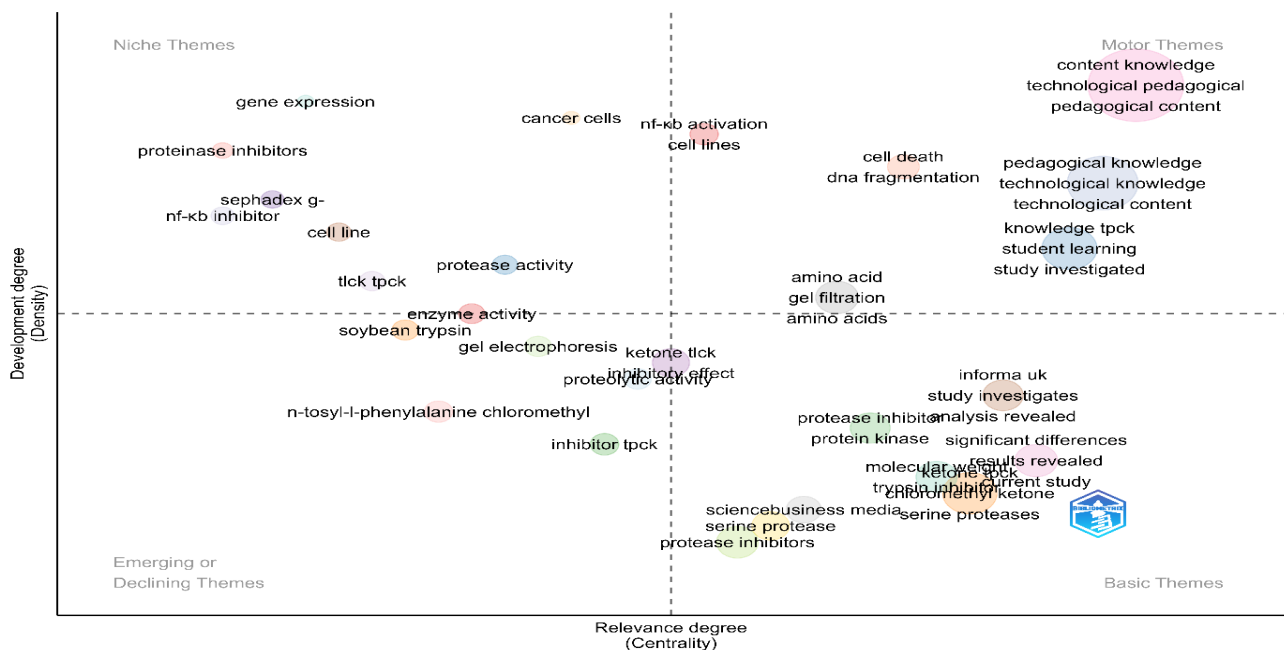


Figure 6. Thematic Map of TPACK Research (1963–2024)

4.1.5. Factor Analysis

Figure 7 presents the conceptual structure map, revealing a triangular distribution of research themes with distinct clustering patterns. Technological content and pedagogical knowledge occupy the upper region, while more specialized topics like structural equations and teacher development appear in the lower left. The map shows a hierarchical relationship between theoretical frameworks (top) and practical applications (bottom). The density of nodes in the lower left quadrant indicates concentrated research activity around teacher preparation and technological integration. At the same time, isolated terms in the right region suggest emerging or specialized research areas.

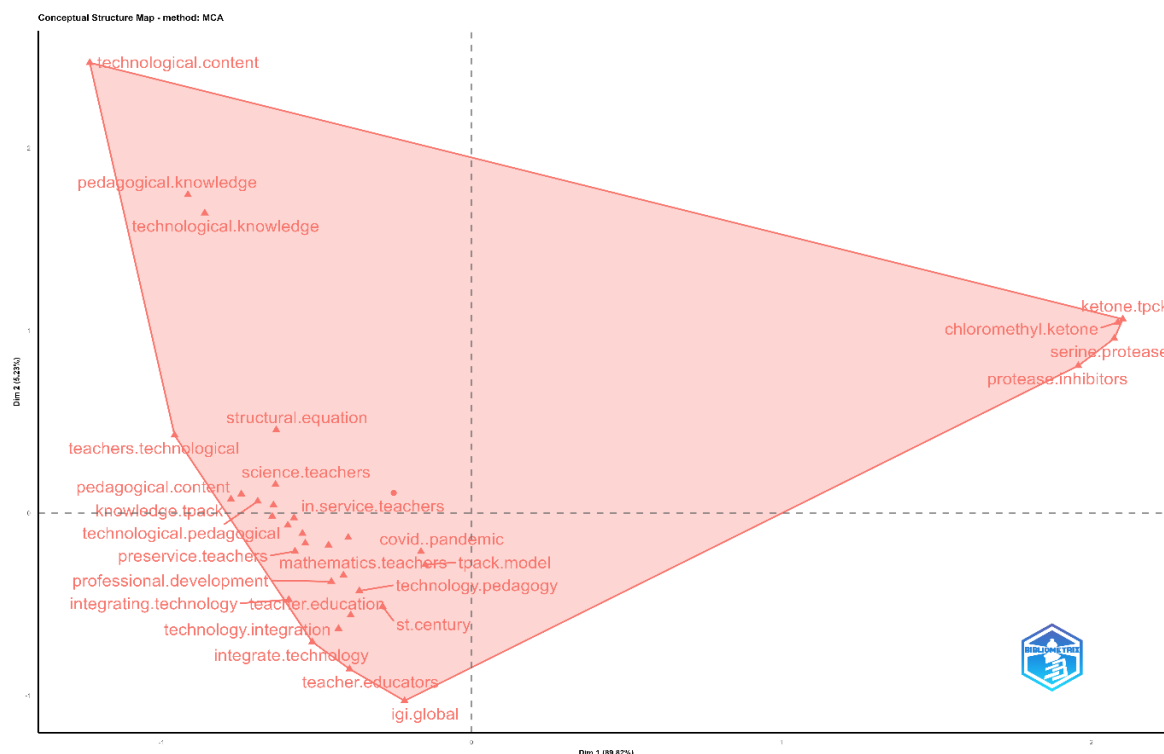


Figure 7. Factorial Analysis by MCA

4.2. Key Contributors and Collaboration Patterns (RQ-2)

Table 2. Most Global Cited Documents

Documents	DOI	TC	TP	NTC
Mishra, P., & Koehler, M. J. (2006). Technological pedagogical content knowledge: A framework for teacher knowledge. Teachers college record, 108(6), 1017-1054.	10.1111/j.1467-9620.2006.00684.x	5559	277.95	20.01
Schmidt, D. A., Baran, E., Thompson, A. D., Mishra, P., Koehler, M. J., & Shin, T. S. (2009). Technological pedagogical content knowledge (TPACK) the development and validation of an assessment instrument for preservice teachers. Journal of research on Technology in Education, 42(2), 123-149.	10.1080/15391523.2009.10782544	1046	61.53	8.95
Angeli, C., & Valanides, N. (2009). Epistemological and methodological issues for	10.1016/j.compedu.2008.07.006	778	45.76	6.66

Documents	DOI	TC	TP	NTC
the conceptualization, development, and assessment of ICT–TPCK: Advances in technological pedagogical content knowledge (TPCK). <i>Computers & education</i> , 52(1), 154-168.	10.3748/wjg.v10.i3.337			
Koehler, M. J., & Mishra, P. (2005). What happens when teachers design educational technology? The development of technological pedagogical content knowledge. <i>Journal of educational computing research</i> , 32(2), 131-152.	10.2190/OEW7-01WB-BKHL-QDYV	758	36.10	6.62
Niess, M. L. (2005). Preparing teachers to teach science and mathematics with technology: Developing a technology pedagogical content knowledge. <i>Teaching and teacher education</i> , 21(5), 509-523.	10.1016/j.tate.2005.03.006	676	32.19	5.91
Harris, J., Mishra, P., & Koehler, M. (2009). Teachers' technological pedagogical content knowledge and learning activity types: Curriculum-based technology integration reframed. <i>Journal of research on technology in education</i> , 41(4), 393-416.	10.1080/15391523.2009.10782536	569	33.47	4.87
Koehler, M. J., Mishra, P., & Yahya, K. (2007). Tracing the development of teacher knowledge in a design seminar: Integrating content, pedagogy and technology. <i>Computers & Education</i> , 49(3), 740-762.	10.1016/j.compedu.2005.11.012	529	27.84	8.04
Koehler, M. J., Mishra, P., Kereluik, K., Shin, T. S., & Graham, C. R. (2014). The technological pedagogical content knowledge framework. <i>Handbook of research on educational communications and technology</i> , 101-111.	10.1007/978-1-4614-3185-5_9	491	40.92	18.52
Falloon, G. (2020). From digital literacy to digital competence: the teacher digital competency (TDC) framework. <i>Educational technology research and development</i> , 68(5), 2449-2472.	10.1007/s11423-020-09767-4	468	78	27.38
Kihoza, P., Zlotnikova, I., Bada, J., & Kalegele, K. (2016). Classroom ICT integration in Tanzania: Opportunities and challenges from the perspectives of TPACK and SAMR models. <i>International Journal of Education and Development using ICT</i> , 12(1).	10.1111/j.1365-2729.2012.00487.x	432	33.23	13.59

TC=Total Citations, TP=Total Citations per Year, NTC=Normalized TC

Table 2 presents the citation analysis revealing a significant scholarly impact on TPACK. Mishra and Koehler's (2006) seminal paper establishing the TPACK framework demonstrates exceptional influence with 5,559 citations and a normalized citation count of 20.01. Schmidt et al.'s (2009) work on TPACK assessment instrument development ranks second with 1,046 citations. The top-cited works predominantly focus on theoretical framework development, assessment methodology, and teacher preparation, with publication dates clustering between 2005 and 2014. The sustained impact of these works is notable, as evidenced by the strong yearly citation rates (TP) of Mishra and Koehler's paper, which averages 277.95 citations per year. The normalized citation metrics (NTC) indicate a powerful relative impact for the foundational papers, with several works maintaining NTC values above 8.0, suggesting their enduring relevance to the field's development.

Table 3. Scientific Production and Citations

Country	Scientific Production	Total Citations	Average Article Citations
USA	690	8959	38.00
CHINA	286	4907	21.50
INDONESIA	231	918	5.20
JAPAN	132	729	18.70
AUSTRALIA	130	1479	20.30
TURKEY	114	856	11.00
SOUTH AFRICA	85	344	7.20
MALAYSIA	83	407	7.50
GERMANY	81	956	18.00
UK	69	776	26.80

Table 3 analyzes international scientific production and reveals significant disparities in research output and impact across countries. The United States leads substantially with 690 publications and 8,959 citations, averaging 38.0 citations per article. China follows with 286 publications and 4,907 citations, while Indonesia ranks third in production (231 articles) but shows lower citation impact (5.2 citations per article). South Africa demonstrates notable citation efficiency, achieving 7.2 citations per article from 85 publications. The data indicates a clear distinction between quantity of output and citation impact, with some countries like Indonesia and Malaysia showing high production but relatively lower citation averages, while others like the UK maintain higher citation impact (26.8) despite fewer publications (69).

4.2.1. Collaboration Network

Figure 8 presents the network visualization that depicts institutional collaborations in the field, with several distinct clusters emerging. Major nodes include China Medical University, National Taiwan Normal University, and Nanyang Technological University, indicating significant research output. The network reveals strong regional collaboration patterns, particularly among East Asian institutions. Node sizes suggest varying levels of publication output while connecting lines demonstrate inter-institutional research partnerships. The spatial distribution indicates both geographic and thematic clustering of research activities.

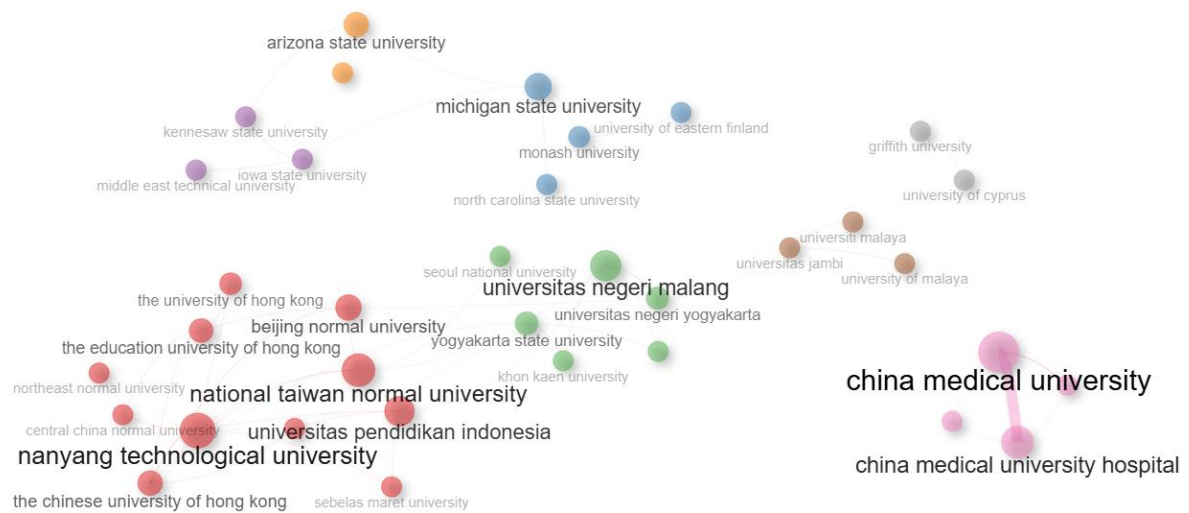


Figure 8. Collaboration Network

4.3. Academic and Societal Impact Comparison (RQ-3)

Table 4 shows an analysis of the top ten highly cited papers in the field of TPACK research, providing insights into their academic and broader societal influence based on citation counts (TC) and Altmetric Attention Scores (AAS). These studies represent key contributions to developing, validating, and practically applying TPACK frameworks and related constructs in education.

The most highly cited paper, "Technological Pedagogical Content Knowledge: A Framework for Teacher Knowledge" by Mishra and Koehler (2006), has an outstanding citation count of 20,473 and a moderate AAS of 33. This foundational work significantly shaped the theoretical discourse on technology integration in education, which demonstrated substantial academic reach, with notable engagement across educational and professional platforms such as Dimensions and Mendeley.

Table 4. Top 10 Highly Cited Papers and AAS

Rank	Title/Authors	TC	AAS	B	C	Co	D	F	I	M	N	PA	PO	W	X	Y
1	Technological pedagogical content knowledge: A framework for teacher knowledge. (Mishra et al., 2006).	20473	33	1	5	2	4576	1	-	19413	2	-	2	-	5	-
2	Technological pedagogical content knowledge (TPACK) the development and validation of an assessment instrument for preservice teachers. (Schmidt et al., 2009).	3648	1	-	1	-	1158	-	-	9682	-	-	-	-	1	-
3	Epistemological and methodological issues for the conceptualization, development, and assessment of ICT-TPCK: Advances in technological pedagogical content knowledge (TPCK). (Angeli & Valanides, 2009).	2431	6	-	7	1	785	-	-	1236	-	-	1	1	-	-
4	What happens when teachers design educational technology? The development of technological pedagogical content knowledge. (Koehler & Mishra, 2005).	2737	3	-	-	-	814	-	-	1242	-	-	-	1	-	-
5	Preparing teachers to teach science and mathematics with technology: Developing a technology	2574	3	-	-	-	723	-	-	1206	-	-	1	-	-	-

Rank	Title/Authors	TC	AAS	B	C	Co	D	F	I	M	N	PA	PO	W	X	Y
	pedagogical content knowledge. (Niess, 2005).															
6	Teachers' technological pedagogical content knowledge and learning activity types: Curriculum-based technology integration reframed. (Harris et al., 2009).	2495	4	-	-	-	638	-	-	11234	-	-	-	2	1	-
7	Tracing the development of teacher knowledge in a design seminar: Integrating content, pedagogy and technology. (Koehler et al., 2007).	1788	9	-	1	1	-	-	-	973	-	-	2	1	-	-
8	The technological pedagogical content knowledge framework. (Koehler et al., 2014).	1315	3	101	-	-	493	-	-	831	-	-	-	1	-	-
9	From digital literacy to digital competence: the teacher digital competency (TDC) framework. (Falloon, 2020).	1499	64	1				1		2876	2		1	1	47	
10	Classroom ICT integration in Tanzania: Opportunities and challenges from the perspectives of TPACK and SAMR models (Kihoza, et al., 2016).	269	269	-	-	-	-	-	-	-	-	-	-	-	-	-

TC=Total Google Scholar Citations, AAS=Altmetric attention score, B=Blogs/Book Overview, C=CiteULike, Co=Connotea, D= Dimensions, F=Facebook pages, I=institutions with syllabi, M=Mendeley, N=New outlets, PA=Patents, PO=Policy source, W=Wikipedia page, X=X users (twitter), Y=YouTube creator (Data retrieved from Altmetric.com on 25 January, 2025)

Schmidt et al. (2009) developed and validated a TPACK assessment instrument, and Angeli and Valanides (2009) addressed epistemological issues in TPACK conceptualization. These studies exhibit high citation counts (3,648 and 2,431, respectively) but relatively lower Altmetric scores, indicating a stronger focus on academic rather than public discourse. These works underscore the importance of TPACK in teacher education and methodological innovation.

Focusing on specific educational practices, Koehler and Mishra's (2005) investigated into design-based learning for TPACK development. Niess's (2005) integrated technology in science and mathematics teaching. Their studies similarly demonstrate high academic citations (2,737 and 2,574, respectively) and highlight the practical implications of TPACK in shaping teacher education and professional development.

Notably, Falloon's (2020) work on the Teacher Digital Competency (TDC) framework exhibits a distinctive profile, with a lower citation count (1,499) but the highest AAS (64) among the analyzed papers. This suggests that the study has resonated more broadly with public and professional audiences, likely due to its emphasis on contemporary digital competencies in complex educational environments.

The remaining studies conducted by Harris et al. (2009) and Kihzoza et al. (2016), contribute additional perspectives on curriculum-based integration and ICT challenges in diverse contexts, albeit with more specialized citation and attention patterns.

4.4. Methodological Approaches in High-Impact Research (RQ-4)

At this stage, content analysis was conducted to explore how high-impact TPACK studies conceptualized, operationalized, and applied the framework. This process used a deductive coding approach, based on predefined categories including research objectives, methods, tools, sample characteristics, and key findings. These categories were informed by prior literature and aligned with the study's overall aim to assess the depth and diversity of methodological practices in TPACK research. The purpose of this analysis was to examine the methodological landscape and extract patterns across influential works, thereby supporting insights related to Research Question 4 (RQ-4): What methodological approaches are most prevalent in high-impact TPACK research?

The content analysis of the ten most-cited TPACK articles used deductive thematic categories drawn from previous bibliometric and conceptual review studies. Each article was examined for its purpose, methodology, tools used, participant/sample information, and major findings. This allowed for a structured comparison of approaches and contributed directly to answering RQ-4, focusing on prevalent methodological strategies in high-impact TPACK literature.

Table 5 comprehensively analyzes the top ten articles in TPACK research, highlighting various objectives, methodologies, tools, and outcomes. The studies collectively aim to conceptualize, develop, and assess TPACK frameworks and related teacher competencies in integrating technology into education. They emphasize the interplay among content, pedagogy, and technology, often advocating for innovative frameworks to improve teacher education. Mishra and Koehler (2006) formalized the TPACK framework to elucidate the interdependencies among these domains, offering a robust model for technology integration. Schmidt et al. (2009) developed and validated an instrument to measure TPACK in preservice teachers, providing a reliable tool for longitudinal studies.

Angeli and Valanides (2009) and Koehler and Mishra (2005) explored transformative methodologies and design-based learning approaches to enhance TPACK development. These studies identified practical strategies, such as Technology Mapping and collaborative problem-solving, to foster competencies in integrating technology within specific educational contexts. Furthermore, Niess (2005) highlighted the challenges and successes of preservice teachers in

developing TPACK, stressing the need for meaningful program designs that align technology integration with disciplinary requirements.

About research extending beyond TPACK frameworks, Falloon (2020) proposed broader constructs like the Teacher Digital Competency (TDC) framework to address ethical, safe, and productive technology use. Meanwhile, Kihoza et al. (2016) assessed ICT integration through TPACK and SAMR (Substitution, Augmentation, Modification, and Redefinition) models, revealing discrepancies in competencies among tutors and teacher trainees in Tanzania, alongside infrastructure and readiness challenges.

These articles underscore the critical importance of robust theoretical frameworks, innovative professional development methodologies, and practical assessment tools in advancing technology integration in education. They collectively contribute to an enriched understanding of the dynamic relationships between pedagogy, content, and technology, offering valuable insights for future research and teacher education practices.

Table 5. Content Analysis of Top 10 Articles in TPACK Research.

No.	Source	Objectives	Methods	Research tools	Data/Sampling	Results/Conclusion
1	Technological pedagogical content knowledge: A framework for teacher knowledge. (Mishra & Koehler, 2006).	To develop a robust theoretical framework; to capture the essential qualities of teacher knowledge necessary for integrating technology into teaching; to address the multifaceted and situated nature of teacher knowledge while highlighting the interplay among content, pedagogy, and technology in learning environments.	The framework development through a long-term research program spanning five years, centered on professional development initiatives for teachers and faculty in higher education; theoretical formulation, practical application, and iterative refinement based on real-world educational contexts.	Examples of teaching approaches based on the proposed framework are used to understand and demonstrate the practical application of TPACK. These examples serve to validate and illustrate the framework's utility in technology integration.	No provision of specific sampling details in this excerpt; grounded in extensive work with teachers and faculty in higher education, involving their professional development and engagement with technology integration.	The study formalizes TPCK as a crucial and multifaceted knowledge framework for integrating technology into pedagogy, emphasizing the dynamic interplay of content, pedagogy, and technology. This framework provides a theoretical foundation for improving technology integration and contributes significantly to educational theory, pedagogy, and teacher education. By offering a structured approach to understanding effective technology use, the TPCK model advances research, professional

No.	Source	Objectives	Methods	Research tools	Data/Sampling	Results/Conclusion
						development, and discussions on enhancing teaching practices through educational technology.
2	Technological pedagogical content knowledge (TPACK) the development and validation of an assessment instrument for preservice teachers. (Schmidt et al., 2009).	To develop and validate a survey instrument specifically designed to measure TPACK in preservice teachers; to assist educators and researchers in assessing and tracking the development of TPACK over time.	Survey development process including item creation, refinement, and validation; A pilot study to test the survey with a sample of preservice teachers; Data analysis to assess the reliability and validity of the survey.	The TPACK survey instrument developed for preservice teachers; The survey encompassing various TPACK knowledge domains and includes multiple items to measure each domain.	A pilot sample of 124 preservice teachers completed the newly developed survey, providing preliminary data to evaluate the instrument's effectiveness.	The study utilized Cronbach's alpha and factor analysis to confirm the reliability and validity of the TPACK survey instrument, leading to necessary revisions, including the deletion or modification of 18 items. The findings indicate that the revised instrument is suitable for assessing TPACK in preservice teachers and holds the potential for longitudinal studies to monitor its development over time. This validated tool offers valuable insights for teacher educators and

No.	Source	Objectives	Methods	Research tools	Data/Sampling	Results/Conclusion
						researchers, supporting the design of effective programs to enhance technology integration in teacher education.
3	Epistemological and methodological issues for the conceptualization, development, and assessment of ICT–TPCK: Advances in technological pedagogical content knowledge (TPCK) (Angeli & Valanides, 2009).	To clarify the epistemology of TPCK and introduce ICT–TPCK as a focused strand; to propose theoretical models for the development and assessment of ICT–TPCK and evaluate their impact on teacher education.	The paper juxtaposes the transformative and integrative views of TPCK, ultimately adopting the transformative perspective. Two theoretical models are proposed: a model for developing ICT–TPCK (Technology Mapping as a situative methodology) and a model for its assessment, including expert, peer, and self-assessment methods. The empirical component involves testing these models in a pre-service	Development Tool: Technology Mapping, a methodology for developing ICT–TPCK. Assessment Tools: Three forms of assessment are used—expert assessment, peer assessment, and self-assessment—to evaluate teachers' competencies in teaching with technology. Design Tasks: Used within the empirical study to facilitate and evaluate ICT–TPCK development.	Pre-service primary teacher education students engaged in two design tasks over a semester; Repeated measures within-subject effects to analyze the impact of the proposed models on their ICT–TPCK competencies.	The study demonstrates significant improvements in ICT–TPCK competencies over the semester, highlighting the effectiveness of integrating the transformative TPCK framework with practical methodologies such as Technology Mapping. The findings validate the proposed ICT–TPCK models as robust tools for developing and assessing teachers' technology integration skills. These results provide

No.	Source	Objectives	Methods	Research tools	Data/Sampling	Results/Conclusion
			primary teacher education course.			a strong foundation for future research to refine and validate the models across diverse educational contexts.
4	What happens when teachers design educational technology? The development of technological pedagogical content knowledge (Koehler & Mishra, 2005).	To investigate the role of authentic, design-based activities in fostering the growth of TPCK among educators.; to examine how participation in design teams addressing real-world instructional problems impacts the development of technological, pedagogical, and content knowledge.	A design-based approach within a faculty development seminar. Faculty members and master's students work collaboratively to develop online courses, engaging in authentic problem-solving tasks; A survey to assess participants' learning and perceptions at the beginning and end of the semester.	A custom-developed survey serves as the primary research tool. The survey assesses various dimensions of participants' experiences, including: Learning environment perceptions, Theoretical and practical knowledge of technology, Course content design, Group dynamics, Growth in TPCK.	Faculty members and master's students participating in a semester-long faculty development seminar; Data collected through pre- and post-surveys to evaluate changes in participants' knowledge and perceptions over time.	The findings reveal that the design-based, collaborative approach effectively enhanced participants' TPCK and technology application knowledge while fostering engagement and improving group dynamics. The study underscores the value of team-based problem-solving in addressing authentic instructional challenges and promoting individual learning. It concludes that learning by design is a powerful method for developing TPCK,

No.	Source	Objectives	Methods	Research tools	Data/Sampling	Results/Conclusion
						emphasizing the importance of authentic, collaborative experiences in professional development for educators.
5	Preparing teachers to teach science and mathematics with technology: Developing a technology pedagogical content knowledge (Niess, 2005).	To examine the development of preservice teachers' TPCK and identify the challenges and successes they encounter while integrating technology into their teaching; to understand the influence of preservice teachers' perceptions of technology integration and its alignment with disciplinary requirements on their TPCK development.	A qualitative approach, analyzing five case studies of student teachers enrolled in a teacher preparation program, providing insights into how preservice teachers develop and apply TPCK while teaching with technology.	The research tools include: Observations of student teachers' teaching practices, Analysis of teaching artifacts and lesson plans, Reflections and interviews with student teachers to assess their perceptions of technology integration and its impact on teaching.	Five student teachers in a multi-dimensional science and mathematics teacher preparation program; cases analysis to provide a detailed understanding of their TPCK development within a program that emphasizes technology integration.	The study highlights challenges and successes in developing preservice teachers' TPCK, with difficulties integrating technology into content and pedagogy contrasted by an improved understanding of technology's role in enhancing teaching and learning. Student teachers' perceptions of the interplay between technology and their discipline emerged as a critical factor in TPCK development. The study concludes that

No.	Source	Objectives	Methods	Research tools	Data/Sampling	Results/Conclusion
						teacher preparation programs must meaningfully integrate technology into teaching experiences to address these challenges and equip future educators with the skills to enhance pedagogy and content delivery effectively.
6	Teachers' technological pedagogical content knowledge and learning activity types: Curriculum-based technology integration reframed (Harris et al., 2009).	To critique technocentric methods of technology integration and to propose the TPACK framework as a holistic alternative; to highlight the interdependence of technology, pedagogy, content, and context in supporting teachers to deliver content-based curricula effectively using	A critical analysis of existing technology integration approaches, comparing these methods to the TPACK framework; proposal of a TPACK-based strategy rooted in prior research on content-specific activity structures, offering practical solutions for professional development.	The TPACK framework serves as the central conceptual tool, alongside the development of TPACK-based "activity types", which are informed by prior research on discipline-specific teaching and learning activities. These activity types are presented as actionable structures to guide teachers in	No provision of specific data or sampling details; analysis grounded in a review of existing research and professional development practices in technology integration.	The analysis reveals that many existing approaches to technology integration overlook the dynamic and interdependent relationships among content, pedagogy, technology, and context. The proposed TPACK framework addresses this gap by offering a more comprehensive and authentic method to support

No.	Source	Objectives	Methods	Research tools	Data/Sampling	Results/Conclusion
		educational technologies.		technology integration.		effective technology integration. The study concludes that combining the TPACK framework with content-specific activity types provides a practical alternative to technocentric methods, recommending its adoption in professional development to enhance the authenticity and effectiveness of technology integration in education.
7	Tracing the development of teacher knowledge in a design seminar: Integrating content, pedagogy and technology (Koehler et al., 2007).	To investigate how TPCK develops over time in the context of a faculty development seminar; to provide insights into how participants move from treating	A semester-long investigation involving a faculty development seminar in which faculty members collaborated with master's students to design online courses.	1. Quantitative Discourse Analysis: Used to analyze 15 weeks of field notes from two design teams to assess changes in participants'	Two design teams comprising faculty members and master's students participated in a 15-week faculty development seminar. The data included detailed field	The analysis reveals a developmental shift among participants from viewing technology, pedagogy, and content as distinct entities to recognizing their complex

No.	Source	Objectives	Methods	Research tools	Data/Sampling	Results/Conclusion
		technology, pedagogy, and content as independent constructs to understanding their interrelated nature. It also seeks to highlight the theoretical, pedagogic, and methodological contributions of TPCK.	Quantitative discourse analysis was applied to field notes collected over 15 weeks to track the evolution of participants' understanding of TPCK.	conceptualization of TPCK. 2. Field Notes: Captured interactions, discussions, and reflections during the seminar, providing rich data for understanding the development of TPCK.	notes documenting their collaborative efforts in designing online courses.	interdependencies. This progression highlights the iterative and exploratory nature of TPCK development, requiring sustained engagement with these interconnected domains. The study concludes that TPCK development is a continuous process, providing significant contributions to the pedagogical, theoretical, and methodological discourse on technology integration while offering a strong foundation for designing professional development programs to enhance subject-specific teaching.

No.	Source	Objectives	Methods	Research tools	Data/Sampling	Results/Conclusion
8	The technological pedagogical content knowledge framework (Koehler et al., 2014).	To provide an in-depth understanding of the TPACK framework, its theoretical foundations, and its application in teacher education; to explore approaches for developing and assessing TPACK in pre-service and in-service teachers while addressing theoretical, pedagogical, and methodological considerations.	A descriptive and analytical approach, synthesizing existing literature and research on TPACK. It reviews the framework's theoretical underpinnings, its relationship to related constructs in educational technology, and various approaches to teacher professional development and TPACK assessment.	1. Literature Review: Synthesizes theoretical and practical contributions to TPACK development and assessment. 2. Assessment Review: Analyzes diverse methods of TPACK measurement, focusing on the interplay between the form and function of these assessments, as well as their reliability and validity.	No report of original data, drawing extensively from research studies, teacher education programs, and professional development initiatives related to TPACK.	The review underscores TPACK's significant impact on teacher education and professional development. It demonstrates its value in bridging theory and practice while highlighting challenges such as contextual variability and the complexity of integrating content, pedagogy, and technology. It reveals diverse professional development approaches and assessment methods for TPACK, with varying reliability and validity depending on their design and purpose. The chapter concludes that TPACK is a valuable framework for guiding effective technology

No.	Source	Objectives	Methods	Research tools	Data/Sampling	Results/Conclusion
						integration, emphasizing the need for well-aligned professional development, improved assessment methods, and further research to refine theoretical models and support teachers in developing TPACK.
9	From digital literacy to digital competence: the teacher digital competency (TDC) framework (Falloon, 2020).	To present a new framework for TDC that extends beyond traditional technical skills and subject-specific digital literacies; to prepare teachers with the holistic knowledge and competencies needed to function ethically, safely, and productively in complex, technology-rich educational environments.	The article employs a conceptual analysis, synthesizing existing research on teacher education, digital competence, and emerging classroom needs. It critiques the narrow focus of existing models and proposes a broader, interdisciplinary approach for developing digital competence among preservice teachers.	1. Literature Review: A comprehensive review of existing frameworks and models for digital competence in teacher education serves as the foundation for the conceptual framework. 2. Conceptual Framework Development: The framework is built upon insights from interdisciplinary research,	No specific empirical data or sampling is discussed; analysis based on existing research and theoretical exploration of digital competence frameworks.	The article highlights significant limitations in current approaches to teacher digital competence (TDC), which often emphasize technical skills or assume indirect development through other disciplines. The proposed framework redefines TDC as a multidimensional construct, incorporating ethical, safe, and productive technology while advocating for

No.	Source	Objectives	Methods	Research tools	Data/Sampling	Results/Conclusion
				emphasizing ethical, safe, and productive engagement in digital environments.		holistic, interdisciplinary approaches within teacher education. It concludes by emphasizing the importance of faculty engagement and providing practical recommendations for implementing the framework to prepare educators for the complex demands of modern classrooms.
10	Classroom integration in Tanzania: Opportunities and challenges from the perspectives of TPACK and SAMR models (Kihiza, et al., 2016).	ICT To assess the opportunities and challenges of integrating ICT into classroom practices within the context of the TPACK and SAMR models; to evaluate the ICT competencies of teacher trainees and tutors in teacher training colleges and to identify factors influencing the effective use of ICT	This study adopted a case study approach involving 206 participants, comprising tutors and teacher trainees from teacher training colleges. It focused on assessing their pedagogical ICT competencies in relation to the TPACK and SAMR frameworks. Data were collected to	The research tools likely included surveys, interviews, and assessments designed to measure participants' ICT knowledge and competencies. These tools were aligned with the constructs of the TPACK and SAMR models to evaluate the integration of ICT	The sample consisted of 206 respondents, including tutors and teacher trainees from teacher training colleges. The study analyzed their pedagogical ICT competencies and knowledge across all TPACK and SAMR constructs, providing insights into their readiness and the challenges they face	The findings of this study indicate that teacher trainees exhibit low pedagogical ICT competencies, hindered by insufficient support for essential ICT tools. At the same time, tutors demonstrate strong knowledge across TPACK and SAMR constructs. Although the TPACK

No.	Source	Objectives	Methods	Research tools	Data/Sampling	Results/Conclusion
		for teaching and learning.	evaluate their skills in using basic ICT tools (hardware, software, and peripherals) and their readiness to integrate technology into educational practices.	in teaching and learning.	in using effectively.	ICT and SAMR models positively influence planning and redesigning learning tasks, their impact is limited by inadequate infrastructure, readiness for change, and insufficient pedagogical ICT skills. The study concludes that addressing these challenges requires a harmonized ICT integration framework for teacher education in Tanzania and further experimental research to explore the practical application of ICT in teaching and learning.

In sum, these findings reflect the dual academic and societal impact of TPACK research, with most contributions achieving significant scholarly recognition and varying levels of engagement in public and professional domains. The interplay between citation metrics and Altmetric indicators highlights the multifaceted influence of these works in advancing educational technology research and practice.

5. Discussion

This study comprehensively analyzes TPACK's evolving role in teacher education, focusing on bibliometric trends, content analysis, and Altmetric Attention Score (AAS) evaluations. The findings reveal a significant growth in TPACK research, particularly from 2010 onwards, with contributions highlighting the importance of integrating technological, pedagogical, and content knowledge in teacher preparation programs. The study also identifies key contributors, influential institutions, and leading publications, illustrating the global collaborative network driving TPACK advancements. Furthermore, the results emphasize the role of Education 5.0 trends in reshaping teacher training to include 21st-century competencies such as creativity, critical thinking, and collaboration.

The study's findings align with prior research demonstrating TPACK's transformative potential in equipping educators with technology-enhanced teaching environments (Mishra & Koehler, 2006; Schmidt et al., 2009). Notably, integrating TPACK into teacher training programs has enhanced teachers' confidence and competence in using digital tools effectively (Izgi-Onbasili et al., 2022). For instance, Niess (2005) analyzed case studies of preservice teachers in science and mathematics, revealing that structured lesson planning activities and reflection tasks helped participants recognize how technology aligned with specific content goals. Similarly, Koehler and Mishra (2005) documented that when teachers collaboratively designed online courses, they exhibited significant growth in their understanding of how to blend technology and pedagogy effectively—highlighting the value of design-based professional development models. Additionally, the study's bibliometric analysis supports earlier findings regarding disparities in TPACK application across teaching stages (Li et al., 2022) and the need for tailored professional development programs (Sarı & Keser, 2021). By examining Altmetric scores, the study highlights the growing societal impact of TPACK research, complementing traditional citation-based metrics and emphasizing the framework's relevance in addressing contemporary educational challenges. Quantitative findings further reinforce this observation. For example, Indonesia ranks third in TPACK publication output but demonstrates a low average citation rate (5.2 citations per article), suggesting regional disparities in research visibility or institutional support. This imbalance has practical implications for capacity-building efforts, indicating a need for tailored interventions and collaborative research opportunities in developing contexts.

Moreover, Falloon's (2020) TDC framework, which received the highest Altmetric Attention Score (AAS = 64), reflects growing public and policy-level interest in teacher digital competencies—suggesting that future training initiatives must address both pedagogical and ethical dimensions of technology use.

While this study provides valuable insights, several limitations must be acknowledged. First, the reliance on Web of Science and Scopus databases may exclude relevant TPACK-related publications indexed in other platforms such as ERIC, Google Scholar, or local/regional databases, potentially limiting the scope of the analysis. Second, although the Altmetric Attention Score (AAS) offers a measure of societal engagement, it does not fully capture the depth or quality of impact, particularly in non-English-speaking or low-digital-visibility contexts. Third, the emphasis on high-impact publications may overlook emerging but innovative studies with lower citation counts.

These limitations open several avenues for future research. Scholars could expand the dataset to include broader sources such as ERIC or preprint repositories, allowing for a more inclusive and dynamic understanding of TPACK's evolution. Future studies might also employ qualitative or mixed-

method approaches to explore TPACK implementation in underrepresented regions or disciplines. Finally, integrating longitudinal data or social network analysis could uncover deeper insights into the development of global collaboration patterns and knowledge diffusion within TPACK research.

The findings have significant implications for research, practice, and policy. a) Future studies should explore TPACK's application in diverse educational contexts, particularly in underrepresented regions and disciplines. Additionally, longitudinal studies could provide deeper insights into the long-term impact of TPACK-focused interventions. b) Teacher training programs must prioritize the development of TPK and TCK through hands-on, discipline-specific training. Collaborative learning approaches, such as design-based activities (Koehler & Mishra, 2005), could enhance pre-service teachers' readiness for digital classrooms. c) Policymakers should invest in structured professional development initiatives that align with Education 5.0 objectives. These programs should emphasize lifelong learning and address infrastructure challenges to ensure equitable access to technology-enhanced education.

The findings align with recent interdisciplinary approaches that integrate cognitive psychology, data science, and inclusive pedagogy into TPACK research, offering a more nuanced framework to support pre-service teacher development in increasingly diverse and technologically complex classrooms (Schmid et al., 2024). Based on our findings, we propose the following recommendations for enhancing teacher training and professional development initiatives:

1. Curriculum Design: Integrate TPACK explicitly into teacher education curricula through modules that balance theory with practical application. Use design-based learning projects where pre-service teachers collaboratively develop lesson plans incorporating TK, PK, and CK.
2. Professional Development: Offer sustained, hands-on workshops focused on building TPK and TCK through real classroom scenarios. Use iterative feedback cycles and reflection tools to help educators recognize and refine their use of TPACK components.
3. Digital Competency Frameworks: Align teacher preparation with broader digital competency models such as Education 5.0 and Falloon's (2020) TDC, emphasizing ethical, safe, and effective technology use.
4. Contextual Adaptation: Develop localized versions of TPACK-based training that address regional needs and disparities—e.g., infrastructure limitations or cultural barriers—based on gaps identified in our country-level citation analysis.
5. Policy Support: Advocate for institutional and policy-level backing to embed TPACK-focused programs across teacher education institutions, emphasizing equity in access to digital tools and resources.

This study addresses the gaps identified in the introduction, particularly the lack of preparedness among pre-service teachers to integrate technology into pedagogy. By providing a nuanced understanding of TPACK's role in teacher education, the findings validate the importance of frameworks like TPACK in bridging theoretical models with practical applications. Additionally, the bibliometric analysis highlights emerging trends and key contributors, complementing the theoretical foundation outlined in the introduction.

5.1. Trends and Thematic Shifts in TPACK Research (RQ-1)

The study revealed a substantial increase in TPACK research since 2010, aligning with the rise of digital and hybrid education. This growth reflects broader shifts in teacher education and technology integration practices, particularly in response to Education 5.0. The prominence of keywords like "digital competence," "teacher training," and "technology integration" suggests a maturing research agenda that increasingly emphasizes interdisciplinary skills. These trends reinforce the role of TPACK

in equipping educators with future-ready competencies. Thematic trends suggest emerging needs in curriculum (e.g., AI, digital ethics).

5.2. Contributions and Collaboration (RQ-2)

The bibliometric analysis highlighted influential authors and institutions, mainly concentrated in East Asia and North America. While certain regions (e.g., the U.S. and China) dominate in productivity, emerging contributors from Indonesia and Turkey show rising engagement despite lower citation impact. These findings suggest both geographical concentration and growing diversification in the TPACK research community, raising opportunities for enhanced cross-regional collaboration. Collaboration patterns can inform institutional benchmarking in teacher training.

5.3. Academic and Societal Impact (RQ-3)

A comparison of citation counts and Altmetric Attention Scores (AAS) reveals that academic influence is concentrated in foundational theoretical work, while societal impact—measured by broader engagement—is limited and uneven. The outlier case of Falloon’s (2020) TDC framework, with the highest AAS, indicates growing interest in ethical and practical digital skills among educators and policymakers. This disconnect underscores a need for research that translates academic insights into actionable public discourse and policy. Low AAS scores indicate a gap between research and classroom/policy impact.

5.4. Methodological Approaches (RQ-4)

The content analysis of highly cited articles shows a strong reliance on conceptual models and survey instruments, with emerging attention to design-based learning and authentic instructional contexts. However, the field lacks methodological depth in areas such as longitudinal evaluation, qualitative classroom research, and cultural contextualization. This suggests future TPACK studies should adopt more diverse and embedded approaches to better capture real-world teacher learning and technology adoption. The dominance of certain methods suggests a need for practice-based teacher training studies.

In conclusion, this study advances the understanding of TPACK’s significance in teacher education by integrating bibliometric, content, and Altmetric analyses. The findings underscore the need for targeted interventions to enhance pre-service teachers’ readiness for technology-integrated teaching, aligning with the demands of Education 5.0. Addressing existing gaps and offering actionable recommendations, this research contributes to the broader discourse on equipping educators with the competencies required for 21st-century education. Future efforts should focus on expanding the scope of TPACK research and fostering global collaboration to ensure its effective implementation in diverse educational contexts.

While the TPACK framework has gained substantial traction in educational research, it has also been subject to several criticisms. Scholars have pointed to conceptual ambiguities, particularly regarding the distinct boundaries between TPK, TCK, and TPACK, which may overlap in practice and hinder precise assessment (Angeli & Valanides, 2009; Schmid et al., 2024). Others argue that TPACK lacks clear guidance for context-specific implementation and overlooks the influence of institutional, cultural, and policy environments on teacher practice. Some have called for a shift toward broader models that integrate ethical, sociocultural, and critical digital literacy perspectives—such as Falloon’s (2020) Teacher Digital Competency (TDC) framework.

In response to these critiques, our multi-dimensional analysis contributes by highlighting how recent TPACK studies are addressing such concerns. The trend topics and thematic mapping (Figure 6 and 7) reveal an evolution toward interdisciplinary and context-aware applications of TPACK, including its adaptation for culturally responsive teaching and education in low-resource

environments. Furthermore, the content analysis of highly cited studies shows increasing emphasis on design-based learning and situated teacher training, aligning with calls for more practical, context-sensitive approaches. These developments suggest that while TPACK may benefit from conceptual refinement, it remains a dynamic and adaptable framework when informed by empirical insights and evolving educational needs.

Based on the findings of this study, several avenues for future TPACK research merit exploration. First, there is a need to examine how TPACK can be adapted for emerging technologies such as AI, AR/VR, and adaptive learning platforms—raising questions like: *How do teachers conceptualize and integrate AI tools within the TPACK framework?* Second, the sociocultural and contextual influences on TPACK integration remain underexplored, particularly in low-resource or multilingual educational settings. Future studies could ask: *What local factors influence the development of TPACK among teachers in underrepresented regions?* Third, our analysis revealed that longitudinal and mixed-methods research remains limited. Investigations could focus on: *How does TPACK evolve over time through professional development, and what are the measurable impacts on student learning outcomes?* Finally, there is a growing call for comparative international studies that examine how TPACK is implemented across different education systems. This could include questions such as: *What are the common and divergent patterns in TPACK adoption between countries with differing digital education policies?* Addressing these questions would not only advance theoretical understanding but also contribute to more inclusive and equitable technology integration practices globally.

In addition to institutional recommendations, our findings suggest several concrete strategies and tools that teachers can adopt to enhance technology integration using the TPACK framework:

- Technology Mapping (Angeli & Valanides, 2009): Teachers can map digital tools to curriculum goals and learning outcomes to ensure alignment with content and pedagogy. This strategy encourages intentional technology use rather than ad hoc adoption.
- Design-Based Learning Projects (Koehler & Mishra, 2005): Educators can engage in collaborative lesson design activities where they iteratively develop, test, and refine technology-enhanced instruction, thereby deepening their understanding of TPACK domains.
- Digital Storytelling (Izgi-Onbasili et al., 2022): Teachers can use digital storytelling tools to help students demonstrate understanding while developing their own TCK and TPK skills in the process.
- Reflection Protocols (Niess, 2005): Structured reflection on the interplay between pedagogy, content, and technology can help teachers assess and adjust their instructional approaches for more integrated learning experiences.
- Activity Type Taxonomies (Harris et al., 2009): Teachers can use predefined activity types linked to content-specific learning goals to select appropriate technology tools—supporting discipline-aligned pedagogical decisions.

Teacher training institutions should incorporate iterative, project-based learning tasks that foster development across all TPACK dimensions and mirror real instructional settings. These strategies provide actionable pathways for teachers to build TPACK capacity in their daily practice, moving beyond theoretical knowledge to meaningful, context-sensitive implementation.

6. Conclusion

This study provides a comprehensive analysis of TPACK's evolving role in teacher education, revealing significant growth in TPACK-related research, particularly after 2010, and underscoring its transformative potential in equipping educators for technology-integrated teaching. Combining bibliometric trends, content analysis, and Altmetric Attention Score evaluations, the findings validate

TPACK's impact while contributing novel insights into its societal influence, mainly through global collaborations and emerging themes. The study highlights the critical alignment of TPACK with Education 5.0 trends, emphasizing its role in fostering 21st-century skills such as creativity, critical thinking, and collaboration. However, the reliance on WoS and Scopus databases, potential limitations in Altmetric evaluations, and the focus on high-impact publications suggest areas for improvement in future research, including broader data sources and diverse methodologies. These findings have significant implications for teacher training programs and policy development, advocating for collaborative, hands-on approaches to professional development and global innovation to ensure equitable technology integration in education. By addressing these challenges, TPACK can continue transforming teaching practices, preparing educators to navigate the complexities of digital learning environments and fostering lifelong learning among students.

Beyond synthesizing existing knowledge, this study offers a unique contribution by mapping both academic and societal impact indicators, revealing emerging global collaborations and methodological patterns. These findings advance the discourse by highlighting underrepresented themes, suggesting a reorientation of future research toward interdisciplinary integration and broader inclusivity in TPACK application.

This study advances the understanding of TPACK's evolving role in teacher education by employing a multi-dimensional analysis that integrates bibliometric trends, content review, and Altmetric impact evaluation. The findings confirm a substantial growth in TPACK-related research, identify influential scholars and institutions, and reveal a shift toward context-sensitive and interdisciplinary applications of the framework. By bridging traditional academic impact with broader societal engagement, the study offers a novel lens to evaluate how TPACK is shaping teacher preparation globally.

In practical terms, the study provides actionable recommendations for teacher education programs, including design-based learning, technology mapping, and the integration of digital storytelling and reflection protocols to enhance teachers' readiness for technology integration. It also proposes policy and curriculum development strategies that align with Education 5.0 goals.

Importantly, the study identifies underexplored areas and proposes specific research questions for future inquiry—ranging from the adaptation of TPACK to emerging technologies like AI, to the influence of cultural and institutional contexts on framework implementation. These insights lay a foundation for ongoing global collaboration and innovation in the field of digital teacher education.

This study applied a multi-dimensional analytical approach—combining bibliometric trend analysis, content review, and Altmetric evaluation—to examine the evolution and impact of TPACK research. The findings reveal a marked growth in TPACK-related publications since 2010, with emerging themes reflecting a shift toward interdisciplinary, digital, and context-aware teaching practices aligned with modern educational priorities. Key contributors and institutions were identified, with collaboration networks showing strong regional clusters and growing international engagement. While academic influence remains centered around foundational theoretical works, societal impact is limited, with only a few studies achieving broader public attention. Methodologically, the field is dominated by conceptual and survey-based designs, though interest in design-based and mixed-methods research is increasing. Despite this, a need remains for more diverse, context-sensitive, and longitudinal approaches to fully capture the complexities of technology-integrated teaching. Overall, the study enhances understanding of TPACK's role in teacher education by uncovering patterns of growth, influence, and methodological orientation, offering practical insights for curriculum development, faculty training, and future research collaborations.

Declarations

Author Contributions. W.C., P.K., U.D., and C.L.: Literature review, conceptualization. W.C., and C.L.: methodology, data analysis. W.C., P.K., U.D., and C.L.: review-editing and writing, original manuscript preparation. All authors have read and approved the published on the final version of the article.

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AI Tool. During the preparation of this work, the authors used ChatGPT and Grammarly for language editing. The authors declare that they reviewed and edited the final output as needed and take full responsibility for the content of the published article.

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About the Contributor(s)

Wirapong Chansanam, Ph.D., is an experienced associate professor with a proven track record of working in information science. He earned his Ph.D. in Information Studies from the Faculty of Humanities and Social Sciences, Khon Kaen University, Thailand, in 2014. He is the Head of the Information Science Department and Chair of the Digital Humanities Research Group at Khon Kaen University. His research interests include information sciences, ontology, knowledge organization systems, data analytics, and linked open data.

Email: wirach@kku.ac.th

ORCID: <https://orcid.org/0000-0001-5546-8485>

Parama Kwangmuang, Ph.D., is an assistant professor and assistant dean for Innovation and Enterprise at the Faculty of Education, Khon Kaen University. He specializes in educational technology, learning innovation, and the integration of cognitive science with teaching and learning. His research focuses on constructivist-based learning models, higher-order thinking skills, and the use of digital technologies, including AI, coding, and 3D animation, to enhance education. He has led several nationally funded research projects and has published extensively in both national and international journals.

Email: parakw@kku.ac.th

ORCID: <https://orcid.org/0000-0002-7364-1381>

Umawadee Detthamrong, D.B.A, is an assistant professor at the College of Local Administration, Khon Kaen University. She holds a Doctor of Business Administration from Khon Kaen University and has expertise in public financial management, corporate governance, bibliometric analysis, and research

on the digital economy. Her work encompasses teaching, research, and academic leadership, with numerous publications in international journals on topics such as fraud detection, retirement planning, and cryptocurrency.

Email: umadet@kku.ac.th

ORCID: <https://orcid.org/0000-0002-5204-1264>

Chunqiu Li, Ph.D., is an associate professor at the School of Government, Beijing Normal University. She received her Ph.D. degree in information science from the University of Tsukuba, Tsukuba, Ibaraki, Japan. Her research interests include digital library, digital humanities, information organization and metadata.

Email: lichunqiu@bnu.edu.cn.

ORCID: <https://orcid.org/0000-0003-1520-1297>

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