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# Research Trends of Artificial Intelligence in TPACK-Based Learning: A Bibliometric Analysis (2020–2025)

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**ABSTRACT**

The integration of Artificial Intelligence (AI) in education has emerged as a growing research trend, particularly within the Technological Pedagogical Content Knowledge (TPACK) framework. This study aims to analyze the development, trends, and intellectual structure of research on AI integration in TPACK-based learning through a bibliometric approach. A total of 406 publications indexed in the Scopus database from 2020 to 2025 were analyzed using VOSviewer to identify publication trends, keyword co-occurrence, co-citation networks, and patterns of international collaboration. The results indicate a significant increase in publication output, particularly after 2022, reflecting the rapid growth of scholarly interest in AI within educational research. Keyword analysis shows that TPACK remains the central research theme, while AI-related topics such as generative AI and ChatGPT have begun to emerge but remain peripheral, indicating that the field is in an early stage of development. Co-citation analysis reveals a strong theoretical foundation dominated by seminal works in TPACK, whereas co-authorship analysis highlights uneven global collaboration, with several countries playing more prominent roles than others. The findings suggest that AI integration within the TPACK framework is evolving rapidly but remains largely conceptual, with limited empirical implementation studies. The novelty of this study lies in providing a comprehensive bibliometric mapping of AI integration within the TPACK framework in the era of generative AI. This study also offers strategic directions for future research regarding adaptive AI–TPACK frameworks, teacher competency development, and ethical considerations in AI-supported learning environments.

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## INTRODUCTION

The rapid development of digital technology has significantly transformed various aspects of human life, including education. Over the past few decades, the use of Artificial Intelligence (AI) in education has expanded considerably, creating new opportunities to improve learning quality, personalize instruction, and enhance the efficiency of teaching and assessment processes (Kul et al., 2026; Riandi et al., 2026). Artificial Intelligence refers to the capability of machines or computer systems to simulate tasks that typically require human intelligence, such as decision-making, speech or image recognition, and problem-solving (Pettersen, 2019; Zhang & Lu, 2021). AI relies on advanced algorithms and computational techniques, including machine learning, natural language processing, and neural networks, to efficiently collect, analyze, and process data. The relationship between AI and education has become increasingly significant, as AI has demonstrated strong potential to transform the design and implementation of teaching and learning (Machmud et al., 2021; Rodríguez-García et al., 2021). In educational settings, AI enables more effective

use of data to support instructional processes through applications such as learning recommendation systems, learning analytics, and intelligent tutoring systems (Yarlagadda, 2025).

A more recent development in this field is the emergence of generative Artificial Intelligence, which can automatically produce various forms of content, including text, images, source code, and other digital media. Generative AI has also contributed to the personalization of learning experiences by enabling adaptive content generation and individualized instructional support for students (Naim & Lestari, 2025). This technology has developed rapidly following the rise of large language models and related AI systems that now underpin many contemporary intelligent applications (Németh et al., 2026). In the context of education, generative AI offers considerable potential to support teaching and learning activities, such as explaining concepts, providing automated feedback to students, and assisting teachers in developing instructional materials (Machmud et al., 2021).

As these technologies continue to evolve, the integration of technology in teaching and learning has become increasingly important. Modern education requires teachers not only to master subject content but also to integrate technology effectively into instructional practice. Effective technology integration can improve student engagement, enrich instructional strategies, and foster the development of twenty-first-century competencies such as creativity, collaboration, and problem-solving (Mishra & Koehler, 2009). Therefore, the use of technologies such as AI should be understood not only from a technical perspective, but also through pedagogical and content-related dimensions.

One of the most widely used conceptual frameworks for understanding technology integration in education is Technological Pedagogical Content Knowledge (TPACK), developed by Mishra and Koehler (2006). The TPACK framework emphasizes that teachers must develop an integrated understanding of three core domains of knowledge: content knowledge, pedagogical knowledge, and technological knowledge (Yang et al., 2025). TPACK provides an important theoretical foundation for understanding how technology can be meaningfully integrated into teaching and learning. Effective technology integration depends not only on teachers' ability to use technological tools, but also on their ability to align those tools with appropriate pedagogical strategies and disciplinary content (Mishra & Koehler, 2009). With the emergence of new technologies such as AI, the TPACK framework has become increasingly relevant for examining how such technologies can be pedagogically integrated into educational practice.

Furthermore, to date, there remains a lack of research mapping global trends in the integration of AI into TPACK-based learning (Deshen et al., 2026; Yang et al., 2025). Without systematic mapping, it is difficult to understand how research trends are evolving, which researchers are the most influential, which countries are most active in research, and what research themes are the primary focus in this field. A bibliometric analysis can address these limitations by quantitatively mapping research developments based on scientific publications. Bibliometric analysis enables researchers to identify research trends, scientific collaboration networks, and emerging research themes within a scientific field of study (Donthu et al., 2021). Therefore, the bibliometric approach is an appropriate method for mapping the development of research on AI in TPACK-based learning.

Unlike previous studies, which generally discussed TPACK and technology integration conceptually, this study offers a comprehensive bibliometric analysis of global research trends on the integration of AI into TPACK-based learning during the 2020–2025 period, using VOSviewer visualizations. This study not only examines publication growth trends but also analyzes co-authorship networks, co-citation structures, and keyword co-occurrence patterns to identify emerging directions in AI-supported pedagogy within the TPACK framework. Based on the identified research gaps, this study aims to analyze global research trends on the integration of Artificial Intelligence into TPACK-based learning using a bibliometric approach. Specifically, this study aims to achieve the following objectives:

1. Identify publication trends related to AI in TPACK-based learning from 2020 to 2025.
2. Identify the most productive authors, institutions, and countries in this research field.
3. Analyze scientific collaboration networks among researchers and institutions.
4. Identify key research themes through keyword co-occurrence analysis.

5. Analyze the direction of research development and future research opportunities regarding the integration of generative AI in TPACK-based learning.

The results of this study are expected to provide a comprehensive overview of research developments in this field and guide future research on the effective integration of AI technology into learning.

## RESEARCH METHOD

This study employs a bibliometric approach to analyze the development of research related to the integration of Artificial Intelligence (AI) into Technological Pedagogical Content Knowledge (TPACK)-based learning. Bibliometric analysis is a quantitative method used to evaluate scientific publications, identify research trends, map intellectual structures, and analyze collaboration patterns within a field of study (Donthu et al., 2021). This study employs both descriptive and evaluative bibliometric approaches.

The research data were obtained from the Scopus database for its broad, multidisciplinary coverage, comprehensive metadata, and strong international reputation in scientific publishing. Scopus is also recognized as one of the largest scientific databases widely used in bibliometric research because it provides standardized citation data and supports comprehensive scientific network analysis (Donthu et al., 2021). The study's timeframe is limited to the period 2020–2025 to capture developments in Artificial Intelligence (AI) research in education, which has seen a significant increase following the acceleration of digital transformation post-COVID-19 and the emergence of generative AI technologies such as ChatGPT and

large language models (Németh et al., 2026; Yang et al., 2025). Data collection was conducted in April 2026 using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, including the identification, screening, eligibility, and inclusion stages (Moher et al., 2009). The data search is illustrated in Figure 1.

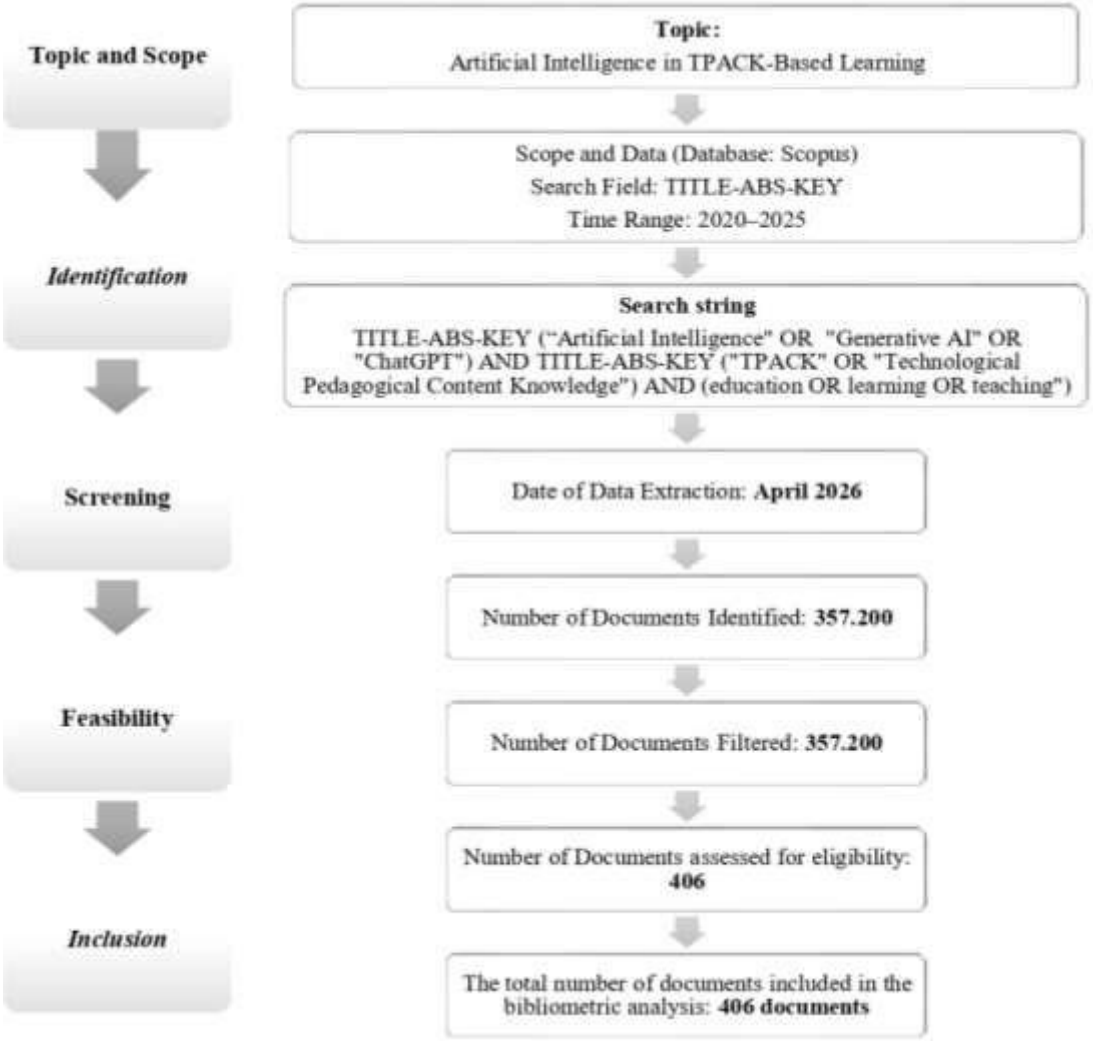



**Figure 1.** PRISMA-Based Data Collection Procedure for Bibliometric Analysis

Figure 1 shows that the first step in the data collection process is identification. The initial search yielded 357,200 publications. Next, a screening process was conducted based on inclusion criteria, namely English-language journal articles relevant to the research topic. After the selection and eligibility evaluation process, 406 publications that met the criteria were identified for further analysis.

Data analysis was performed using several bibliometric software tools. Microsoft Excel was used to process descriptive data and analyze publication trends, country distribution, and citation trends, owing to its effective and flexible capabilities for managing numerical data (Akpan, 2024; Chapke & Chandankhede, 2024; Lindquist & Sulewski, 2024; Suprapto et al., 2024). VOSviewer was used to visualize bibliometric networks, such as co-authorship, co-citation, and keyword co-occurrence, because it can systematically and interactively display relationships among research data and identify the direction of AI research development in TPACK-based learning (Safitri & Admoko, 2024; Safitri & Mubarok, 2024). Additionally, the Publish or Perish (PoP) software was used to efficiently calculate citation indicators, such as the h-index and g-index, from the obtained publication data (Dymkova, 2022; Handayani et al., 2022). The use of PoP in bibliometric research is considered effective for evaluating the scientific impact and productivity of a research field. The analysis results are then visualized using VOSviewer to identify the direction of AI research development in TPACK-based learning.

## RESULTS AND DISCUSSION

### Results

A total of 406 publications related to the use of Artificial Intelligence in TPACK-based learning, published between 2020 and 2025 and meeting the predefined inclusion criteria, were selected for descriptive bibliometric analysis. The analysis further examines publication and citation trends, country and journal distributions, and the major research themes in this field.

#### *Publication Trend by Year*

The publication trend of studies on Artificial Intelligence in TPACK-based learning from 2020 to 2025 was analyzed using annual publication counts. A total of 406 publications were classified according to their year of publication, as presented in Figure 2.

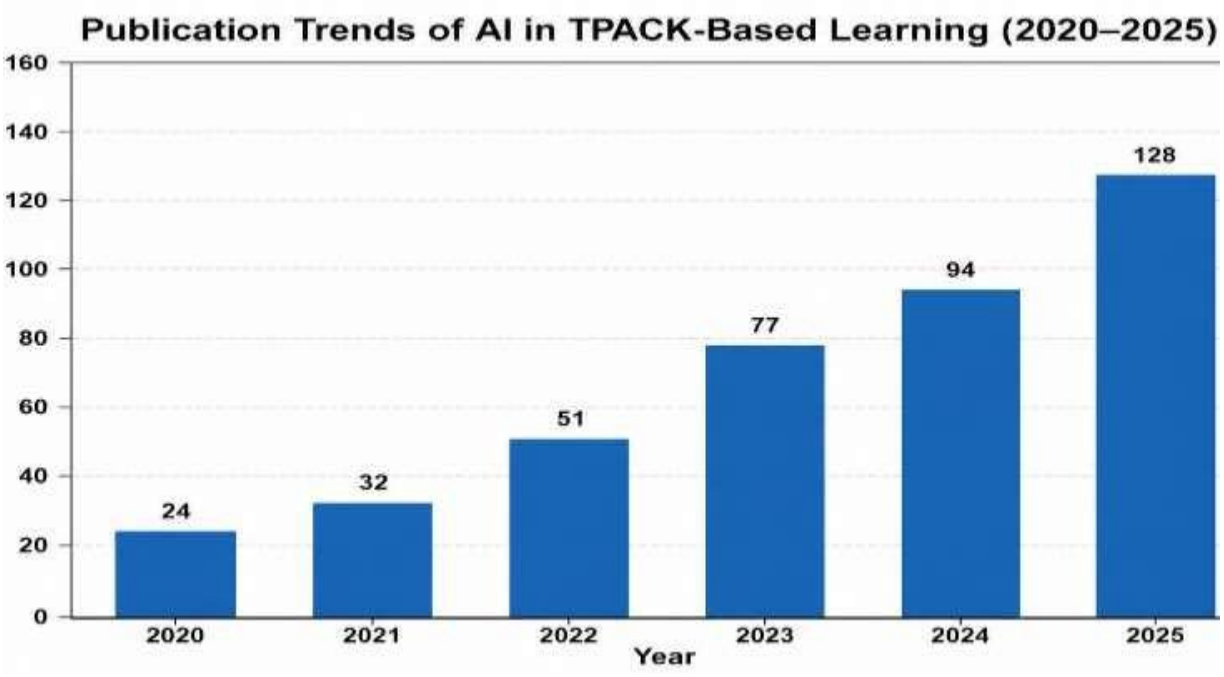



**Figure 2.** Publication Trends of AI in TPACK-Based Learning (2020–2025)

As shown in Figure 2, the publication trend demonstrates not only a consistent increase over time, but also a clear acceleration in research output from year to year. During the initial phase, from 2020 to 2021, the number of publications increased from 24 to 32, indicating relatively modest growth and reflecting the emerging stage of AI research within the TPACK framework. From 2021 to 2022,

publication output increased more substantially to 51 publications, suggesting that this topic began to attract broader scholarly attention.

The most notable change occurred between 2022 and 2023, when the number of publications rose sharply from 51 to 77. This increase may be interpreted as an inflection point, likely influenced by the rapid advancement of Artificial Intelligence technologies, including the emergence and adoption of various AI tools in educational contexts. This upward trend continued from 2023 to 2024, with the number of publications increasing to 94, indicating sustained and growing academic interest in this field.

The peak was reached in 2025, with publication output rising to 128, the largest annual increase observed during the period. This suggests that the field has entered a phase of rapid expansion, with an increasing number of researchers exploring the integration of AI into TPACK-based learning. Overall, the pattern shown in the figure reflects a transition from an emerging research area to a more mainstream field of inquiry, characterized by strong growth and no clear signs of saturation. This trend indicates substantial opportunities for future research, both in theoretical development and in practical implementation within educational settings.

***Network Visualization Using VOSviewer***

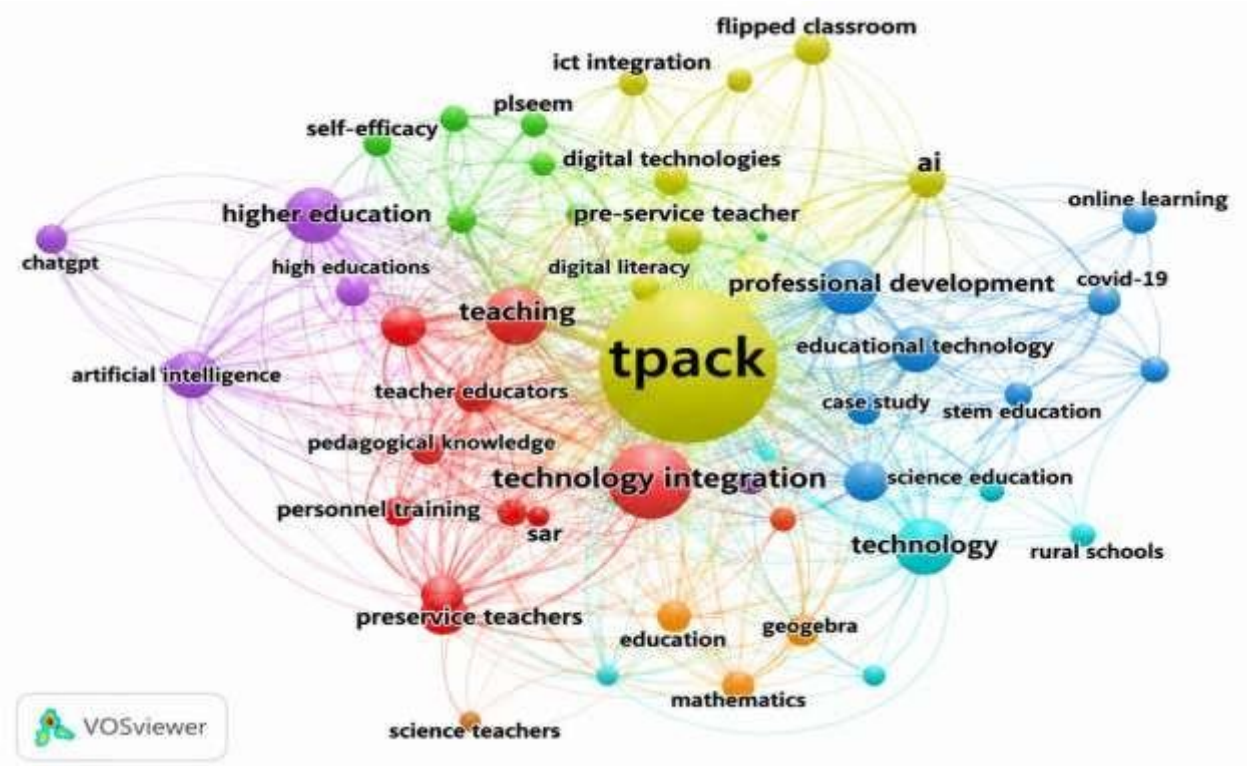



**Figure 3.** Keyword Co-occurrence Network in AI and TPACK Research Using VOSviewer

Based on the co-occurrence network visualization generated with VOSviewer, a clear pattern of relationships among keywords emerges, representing the conceptual structure of research on TPACK. In this network, the keyword TPACK (Technological Pedagogical Content Knowledge) appears as the largest node and occupies the central position, indicating that TPACK serves as the primary focus and conceptual anchor connecting various themes in technology-based educational research.

The visualization also reveals the formation of several thematic clusters representing interconnected research topics. The first cluster focuses on technology integration in teaching and learning, characterized by keywords such as *technology integration*, *pedagogical knowledge*, *teacher educators*, *SAMR*, and *preservice teachers*. This cluster highlights that a substantial portion of the literature emphasizes how technology is implemented in instructional practice and how teachers develop competencies for effective technology integration.

The second cluster is associated with teacher competence and digital literacy, including keywords such as *digital literacy*, *self-efficacy*, *pre-service teacher*, and *digital technologies*. This finding suggests that individual teacher capacities, particularly digital literacy and self-confidence, play a critical role in the development and application of TPACK.

The third cluster relates to educational technology and STEM-based learning, represented by keywords such as *educational technology*, *science education*, *STEM education*, *online learning*, and *COVID-19*. The presence of the keyword *COVID-19* indicates a shift in research attention toward online learning in response to global disruptions, further reinforcing the importance of technological competence in education.

Another cluster highlights teacher professional development, with keywords such as *professional development*, *ICT integration*, and *flipped classroom*. This cluster suggests that improving teacher quality through training and instructional innovation constitutes an essential component of TPACK development.

In addition, one cluster links TPACK to emerging technological developments, particularly Artificial Intelligence, as indicated by keywords such as "artificial intelligence" and "ChatGPT". Although the nodes in this cluster are relatively small, their presence suggests that AI integration in education is an emerging trend that has begun to gain attention and may become a major research focus in the future.

On the other hand, keywords such as *mathematics*, *GeoGebra*, and *education* indicate the application of TPACK in specific disciplinary contexts, particularly mathematics education. This suggests that TPACK research is not only conceptual in nature but also widely applied across various academic disciplines.

Overall, the co-occurrence analysis shows that TPACK research is primarily dominated by themes related to technology integration, teacher competency development, and the application of technology in science and STEM education. Meanwhile, topics related to Artificial Intelligence remain in the early stages of development, indicating substantial opportunities for future research on integrating intelligent technologies within the TPACK framework.

**Table 1.** Top 10 Most Cited Articles

| Title | Writer | Year | Source | Publisher | Cites |
|---|---|---|---|---|---|
| Pre-Service Teachers' GenAI Anxiety, Technology Readiness, and AI Integration | Wang K.; Ruan Q.; Zhang X.; Fu C.; Duan B. | 2024 | Behavioral Sciences | MDPI | 98 |
| A personalized learning system-supported professional development for teachers | Chaipidech P.; Srisawasdi N.; Kajornmanee T.; et al. | 2022 | Computers and Education: Artificial Intelligence | Elsevier | 96 |
| Assessing the digital competence of educators in higher education | Miguel-Revilla D.; Martínez-Ferreira J.M.; Sánchez-Agustí M. | 2020 | Australasian Journal of Educational Technology | ASCILITE | 90 |
| Fresh perspectives on TPACK: pre-service teachers | Valtonen T.; Leppänen U.; Hyypiä M.; et al. | 2020 | Education and Information Technologies | Springer | 88 |
| Examining teachers' behavioral intention for AI integration | Khong H.; Celik I.; Le T.T.T.; et al. | 2023 | Education and Information Technologies | Springer | 77 |
| Online teaching during the COVID-19 pandemic: challenges and opportunities | DeCoito I.; Estaiteyeh M. | 2022 | Disciplinary and Interdisciplinary Science Education Research | Springer | 72 |
| Enhancing English as a Foreign Language (EFL) learning using technology | Tseng Y.-C.; Lin Y.-H. | 2024 | Electronic Journal of e-Learning | Academic Conferences and Publishing International | 69 |
| Technological Pedagogical Content Knowledge (TPACK) in education | Santos J.M.; Castro R.D.R. | 2021 | Social Sciences and Humanities Open | Elsevier | 64 |
| Development and validation of teacher artificial intelligence competency | Chiu T.K.F.; Ahmad Z.; Çoban M. | 2025 | Education and Information Technologies | Springer | 62 |
| Teachers' role in digitalizing education: an updated perspective | Wohlfart O.; Wagner I. | 2023 | Educational Technology Research and Development | Springer | 59 |

Based on the top 10 most-cited articles, the research trend in Artificial Intelligence (AI) within TPACK-based learning is predominantly characterized by studies focusing on teacher readiness, competence, and technology integration. The most highly cited articles generally address themes such as teacher readiness, AI competency, and technology integration, indicating that teachers play a central role in the effective implementation of AI in educational settings. In addition, several studies emphasize the importance of teacher professional development through AI-supported learning systems, as well as the enhancement of digital competencies in higher education contexts.

From a temporal perspective, most of these highly cited studies were published between 2020 and 2024, indicating a substantial increase in research activity following the COVID-19 pandemic, when digital transformation in education became an urgent global priority. This trend reinforces the view that AI integration within the TPACK framework has developed rapidly in response to changes in global educational systems.

Furthermore, the prominence of reputable journals from Springer, Elsevier, and MDPI suggests that this topic has gained considerable academic relevance and international significance. Overall, these findings indicate that current research is no longer primarily focused on AI as a standalone technology, but rather on how AI can be effectively integrated through pedagogical competence and teacher readiness within the TPACK framework. This trend also points toward emerging more advanced conceptual developments, such as AI-TPACK and the integration of generative AI in education.

***Citation Network of Publications***

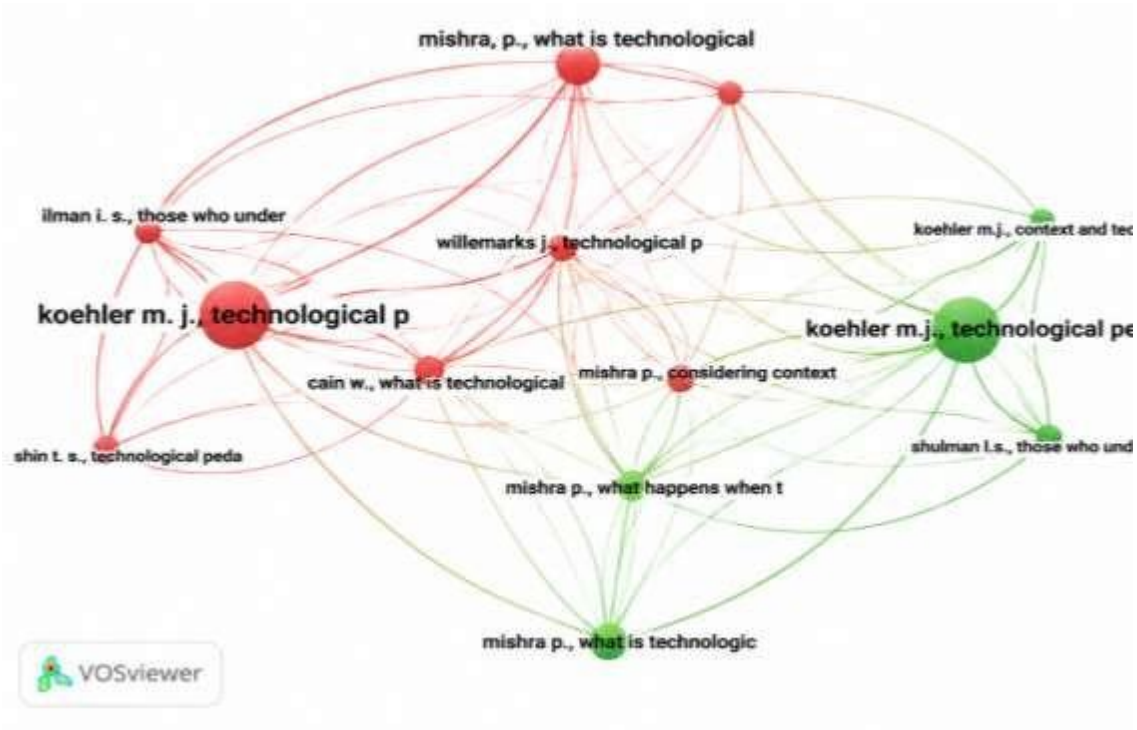



**Figure 4.** Citation Network of Publications Related to TPACK Research

Based on the figure, the cluster analysis of the citation network provides a more detailed view of the intellectual structure of the TPACK field, revealing two major poles that differ not only thematically but also in terms of scholarly development. The red cluster represents a strong conceptual foundation, in which the works of Matthew J. Koehler and Punya Mishra on Technological Pedagogical Content Knowledge occupy the central position, as indicated by their large node sizes and high connectivity. These works are closely linked to the earlier ideas of Lee S. Shulman on Pedagogical Content Knowledge (PCK), which serve as a key bridging node connecting foundational and contemporary perspectives. The dense interconnections within this cluster indicate a high level of co-citation, suggesting that these publications serve as the intellectual core and theoretical foundation of most TPACK research. In addition, the presence

of authors such as Scott Willermark and William Cain around the center of the cluster suggests the reinforcement and expansion of foundational TPACK concepts through diverse theoretical perspectives.

In contrast, the green cluster reflects a more applied and contextual dimension of TPACK development. Although still centered around the work of Mishra and Koehler, the focus in this cluster shifts toward issues such as context, implementation, and the practical application of TPACK in authentic teaching environments. Nodes such as *considering context* and *what happens when technology…* suggest that research in this cluster increasingly explores environmental variables, teacher readiness, and technology integration in more complex instructional settings. Compared with the red cluster, the connections among nodes in this cluster are more dispersed, indicating greater thematic diversity and methodological variation.

Most importantly, the strong interconnection between these two clusters, evidenced by numerous links across cluster boundaries, suggests that although TPACK research has evolved toward practical application, its theoretical foundations remain central. In other words, the field has not undergone conceptual fragmentation but rather has undergone a continuous evolution from theory to practice. In a broader context, research on Artificial Intelligence within TPACK likely occupies this transitional space or may even represent an extension of the green cluster, as AI functions as an emerging technology that both enriches TPACK implementation and potentially reshapes its conceptual boundaries. Overall, this cluster map not only identifies the most influential scholars in the field but also illustrates how TPACK research has evolved from conceptual foundations toward more complex, contextual, and technology-driven educational innovation.

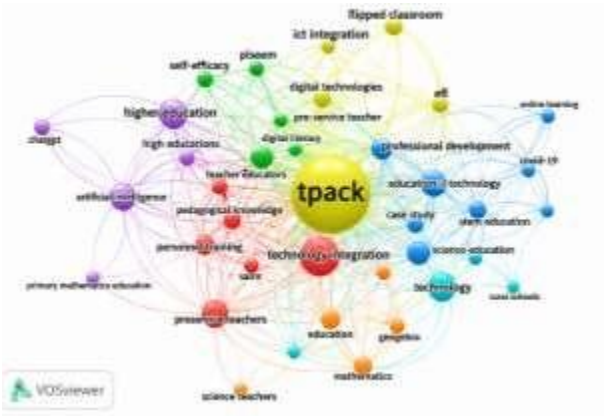



**Figure 5.** Keyword Network Visualization of TPACK Research Themes

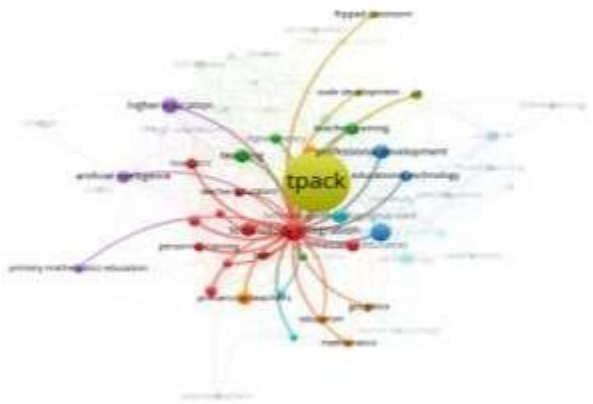



**Figure 6**. Co-occurrence Visualization of Technology Integration and TPACK

Figure 5 presents a keyword co-occurrence map illustrating the relationships among research topics in the field of Technological Pedagogical Content Knowledge (TPACK). Based on the visualization, the keyword *TPACK* appears as the central and largest node, indicating both the highest frequency of occurrence and its dominant role within the research network. This confirms that TPACK serves as the primary conceptual framework in studies concerning technology integration in education.

From a clustering perspective, several thematic groups can be identified based on color differentiation. One cluster focuses on teacher competency development and includes keywords such as *professional development*, *teacher knowledge*, and *technological content knowledge*. This cluster indicates that a substantial portion of the literature focuses on strengthening teachers' capacity to integrate technology effectively in instructional settings. Another cluster emphasizes implementation-related issues, as represented by keywords such as technology integration, training, and engineering education, highlighting the practical application of technology in teaching and learning.

In addition, another cluster reflects diverse educational contexts, including keywords such as *pre-service teacher*, *higher education*, *online learning*, and *rural schools*. This suggests that the application of TPACK has expanded across multiple educational levels and instructional settings. Notably, keywords such as *artificial intelligence* and *ChatGPT* also appear at the periphery of the network. Their peripheral position indicates that AI-related topics remain emerging themes, although they have begun to enter the broader TPACK research discourse.

Overall, this map demonstrates that TPACK research has developed in a multidimensional manner, encompassing conceptual foundations, competency development, practical implementation, and diverse educational contexts. The emergence of Artificial Intelligence-related topics suggests a new direction in the field, with strong potential to further enrich TPACK research.

The second visualization also presents a keyword co-occurrence map, but with a network structure that appears more complex and more centralized than the previous figure. Once again, *TPACK* occupies the central position as the largest node, reinforcing its role as the conceptual core of the research network. However, in this visualization, the relationships between *TPACK* and other keywords, such as technology integration, education, and teacher training, appear stronger and more direct, as indicated by denser, more concentrated connections extending from the central node.

From a clustering perspective, the overall structure is relatively similar to the previous visualization, but greater emphasis is placed on teacher professional development and training, as reflected in keywords such as *professional development*, *teacher training*, and *scale development*. This suggests that the literature is no longer limited to conceptual and implementation-oriented discussions but has increasingly expanded to include measurement, evaluation, and the development of TPACK-related instruments. In addition, the presence of keywords such as *educational technology*, *curriculum*, and *mathematics* indicates a growing expansion into discipline-specific applications and curriculum integration.

Compared with the previous figure, several distinctions can be identified. In the first visualization, the network structure appears more dispersed, with relatively well-separated clusters and emerging topics such as *artificial intelligence* and *ChatGPT* positioned at the periphery. This suggests that the field is characterized by broader thematic diversity and the emergence of new research directions. In contrast, the second visualization appears more centralized and integrated, with stronger connections between *TPACK* and its core dimensions, particularly technology integration and teacher development.

Thus, the first figure represents the thematic diversity and expansion of TPACK research, including the emergence of new topics such as Artificial Intelligence, whereas the second figure reflects the consolidation and deepening of research on the core dimensions of TPACK, particularly in terms of implementation, teacher training, and competency development. Together, these two visualizations provide complementary perspectives: the first illustrates the field's expanding direction, while the second demonstrates the strengthening of the internal conceptual structure of TPACK research.

***Co-Citation Analysis***

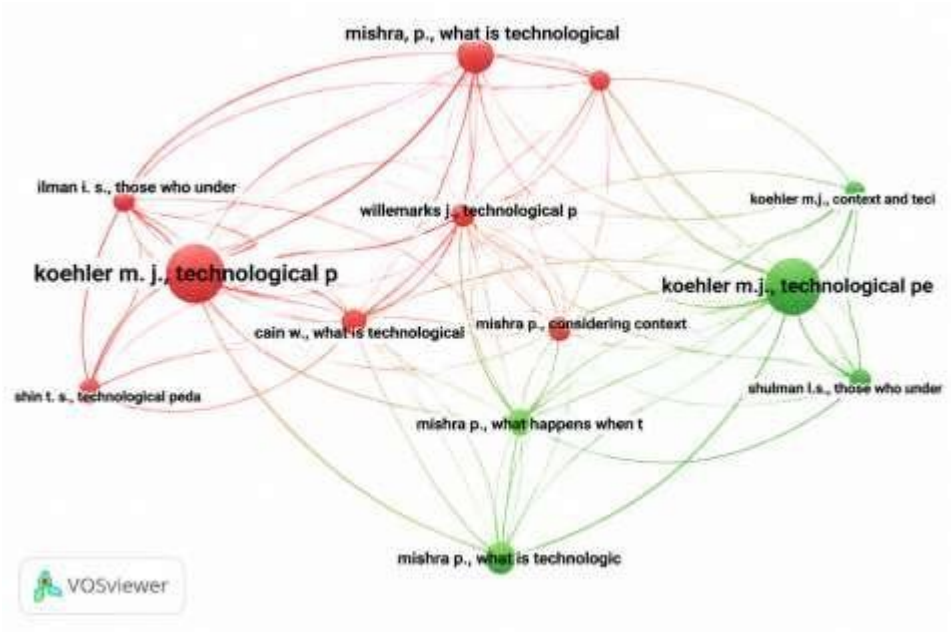



**Figure 7**. Authors' Co-Citation Network in TPACK Research Using VOSviewer

Based on the co-citation visualization using VOSviewer, patterns of interconnection between references can be observed, which form the primary foundation of research related to TPACK. This map

indicates that several authors have a high level of co-citation, signifying a significant contribution to the development of the TPACK concept.

Generally, the co-citation network is divided into two main clusters, namely the red and green clusters, which represent groups of literature with conceptual proximity. The first cluster (red) is dominated by early works on the basic conceptualization of TPACK, such as those by Matthew J. Koehler and Punya Mishra, which discuss its definition and theoretical framework. Furthermore, Lee S. Shulman's contributions laid the initial foundation through the concept of Pedagogical Content Knowledge (PCK). The presence of this literature indicates that the development of TPACK is inseparable from the evolution of the PCK concept, which serves as the basis for integrating pedagogy and content.

Meanwhile, the second cluster (green) reflects the further development of the TPACK concept, which is more contextual and applied. Works such as those by Punya Mishra on "considering context" and the development of TPACK in learning practice demonstrate an expansion of perspective, from a mere conceptual framework to implementation across diverse educational contexts. Similarly, the work of Matthew J. Koehler, which highlights the relationship between technology and the learning context, reinforces that TPACK is dynamic and contextual.

The strong connection between Punya Mishra and Matthew J. Koehler within both clusters indicates that these two figures form the intellectual core of the TPACK field. Furthermore, the inclusion of Lee S. Shulman suggests that TPACK research remains heavily reliant on PCK as its epistemological basis.

Interestingly, other references, such as Willermark and Cain, also appear in the network, indicating contributions to re-examining and critiquing TPACK, particularly regarding the definition and boundaries of technology in learning. This signifies a dynamic in theoretical development, where there is not only adoption but also critical reflection on the TPACK framework.

Overall, this co-citation analysis shows that the scientific structure of TPACK is built upon two main layers, namely: (1) a theoretical foundation derived from the integration of PCK into a technological context, and (2) conceptual development that is more contextual and applicable in educational practice. Thus, it can be concluded that TPACK research has a strong theoretical basis whilst continuing to evolve in line with the needs and dynamics of technology in education.

***Analysis of Co-authorship by Country***

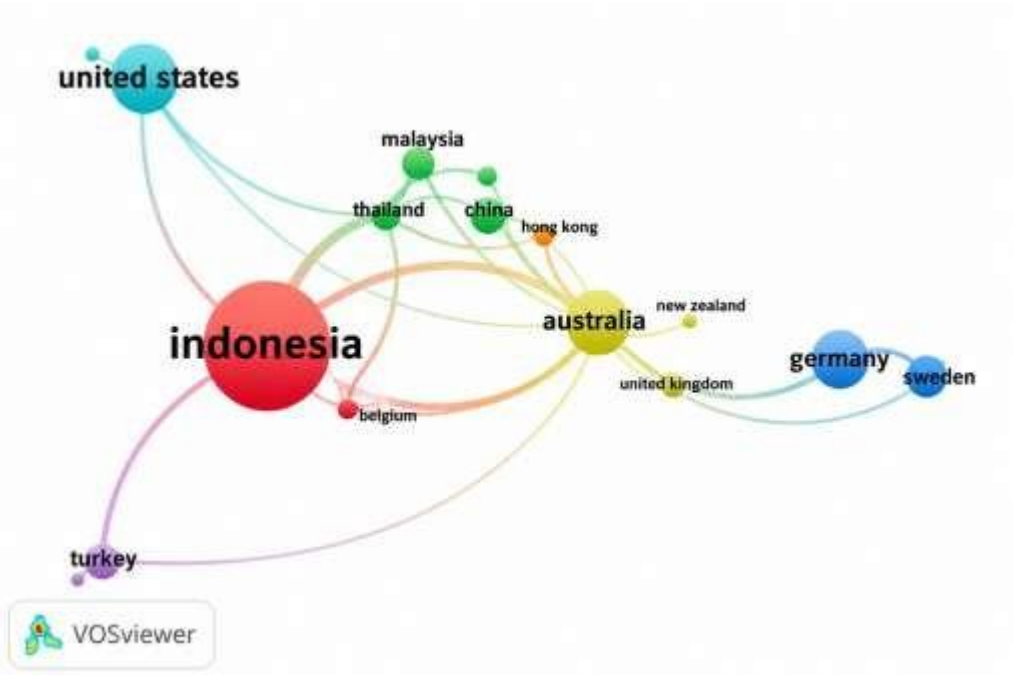



**Figure 8.** International Co-authorship Network in TPACK Research

Based on a visualization of the international collaboration network using VOSviewer, patterns of international cooperation in TPACK-related research are evident. Node size represents publication output, whilst lines (links) indicate the strength of collaboration between countries. The analysis reveals that Indonesia is the country with the most dominant contribution, as indicated by the largest node size. This

suggests that Indonesia has a high level of publication output in the field of TPACK. Furthermore, Indonesia has connections with several other countries, such as the United States, Australia, and Thailand, indicating international collaboration, though this remains limited to a few key partners.

On the other hand, Australia appears to act as a hub within the global collaboration network. This country has links with various nations such as the United Kingdom, New Zealand, and Asian regions, including China and Malaysia. This position suggests that Australia plays a strategic role in bridging cross-regional collaboration. Furthermore, Germany and Sweden form a distinct cluster, indicating regional collaboration within Europe. However, this cluster's connectivity with other countries is relatively limited, suggesting that collaboration remains predominantly regional.

Countries in Asia, such as China, Thailand, and Malaysia, also demonstrate a fairly active collaborative network, particularly with Australia. This indicates that the Asian region is emerging as a key hub for growth in TPACK research, particularly in developing nations. Meanwhile, Turkey appears in a peripheral position with limited connections. This suggests that the country's international contributions and collaboration in this field remain relatively low.

**Discussion**

The results of the bibliometric analysis show that research on integrating Artificial Intelligence (AI) into the Technological Pedagogical Content Knowledge (TPACK) framework has grown significantly in recent years. The exponential increase in publications indicates that this topic has transitioned from an emerging stage to a rapid-growth stage. The surge in publications after 2022 can be attributed to the rapid development of generative AI technologies, such as ChatGPT, which are increasingly adopted in educational contexts. This finding is consistent with previous studies suggesting that technological innovation often catalyzes shifts in educational research trends and pedagogical transformation (Zawacki-Richter et al., 2019).

From a conceptual-structural perspective, the results of the keyword co-occurrence analysis indicate that TPACK remains the central hub within the research network. This confirms that TPACK continues to serve as the dominant theoretical framework for understanding technology integration in education. However, the emergence of keywords such as "artificial intelligence" and "ChatGPT," despite still occupying peripheral positions in the network, indicates an expansion of the research domain. This peripheral position suggests that the integration of AI into TPACK remains in its early stages, thereby opening substantial opportunities for further exploration, particularly in pedagogical implementation. This finding aligns with Mishra and Koehler's (2009) argument that TPACK is a dynamic framework that evolves in tandem with technological advancement.

Furthermore, the analysis indicates that the current research focus is no longer limited to technological aspects alone, but has shifted towards teacher-related competencies, including digital literacy, self-efficacy, and professional development. This reinforces the view that the successful integration of technology, including AI, is highly dependent on teachers' readiness and capacity. Similar findings were reported by Yang et al. (2025), who emphasized the importance of teacher preparedness and adaptive competencies in AI-supported learning environments. These findings are also consistent with TPACK theory, which emphasizes the importance of balancing technological, pedagogical, and content knowledge. In this context, AI cannot be effectively implemented without adequate pedagogical competence and contextual understanding.

From an intellectual structure perspective, the co-citation analysis indicates that the field of TPACK is built upon a strong theoretical foundation, particularly drawing on the seminal works of Mishra, Koehler, and Shulman. The conceptual clusters that emerge suggest continuity between the concept of Pedagogical Content Knowledge (PCK) and its evolution into TPACK. Meanwhile, the emergence of applied clusters indicates that current research is gradually shifting from conceptual discussions toward practical implementation in various educational settings. This demonstrates that the development of TPACK research occurs progressively rather than through a complete paradigm shift. Such findings support previous studies that view TPACK as a flexible framework capable of adapting to emerging educational technologies.

Meanwhile, an analysis of co-authorship by country reveals that research contributions are dominated by a few countries, with Indonesia among the main contributors. Nevertheless, patterns of international collaboration remain limited and uneven. Countries such as Australia act as key hubs within the global network, whilst several other countries remain on the periphery. This indicates a collaboration gap that could influence global research development.

Compared to previous studies, these findings indicate a shift in focus from general technology integration toward the integration of intelligent technologies, particularly AI. Earlier studies mainly emphasized technologies such as e-learning platforms and multimedia tools, whereas current studies increasingly explore the role of AI in supporting adaptive learning, personalized learning, automated assessment, and intelligent tutoring systems. Therefore, TPACK appears to be undergoing a conceptual expansion toward what may be referred to as AI-TPACK. Theoretically, this indicates that traditional TPACK constructs may need to be adapted to address AI-related competencies, ethical considerations, and data literacy. Practically, these findings imply that educators and institutions should not only focus on technical AI skills but also develop pedagogical and ethical frameworks for meaningful AI integration in learning environments.

Overall, this study demonstrates that research on AI integration within TPACK-based learning is currently in a highly dynamic transitional phase. On one hand, the field is supported by a strong theoretical foundation; on the other hand, it presents substantial opportunities for innovation and conceptual development. The rapid expansion of AI technologies in education suggests that future studies should place greater emphasis on empirical implementation, ethical implications, and the development of adaptive pedagogical models that integrate AI meaningfully into educational practice.

## CONCLUSION

This study examines the global development of the integration of Artificial Intelligence (AI) into Technological Pedagogical Content Knowledge (TPACK)-based learning through a bibliometric analysis of 406 publications from the period 2020–2025. The results of the analysis indicate that this field is experiencing rapid growth and has transitioned from an early stage to rapid expansion. TPACK remains the primary conceptual framework dominating the research structure, whilst AI integration is beginning to emerge as a new, developing direction, albeit still in its early stages.

Structurally, research in this field is built upon a strong theoretical foundation, particularly drawing on PCK and TPACK concepts, yet has evolved towards a more applied and contextual orientation. The research focus also indicates a significant shift from mere technology use towards strengthening teachers' competencies, such as digital literacy, technological readiness, and professional development. Furthermore, an analysis of international collaboration reveals that whilst there are significant contributions from several countries, global cooperation patterns remain uneven and fragmented.

The key implication of these findings is that the success of AI integration in learning is not solely determined by the availability of technology but is heavily dependent on teachers' ability to integrate it in a pedagogically and contextually appropriate manner. Therefore, there is a need to develop more adaptive learning models, such as AI-TPACK, that can accommodate the characteristics of intelligent technology in educational practice.

Moving forward, research in this field should focus on strengthening empirical studies regarding the implementation of AI in learning design, the development of AI-based teacher competencies, and the exploration of ethical issues and the long-term impacts of using intelligent technologies in education. Thus, this research not only provides a comprehensive overview of trends and the field's structure but also offers strategic directions for the development of research and educational practice in the era of AI-driven digital transformation.

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