

Visualization Analysis of Global Teacher TPACK Research based on CiteSpace

Gengsheng Xiao, Simin Huang*

School of Languages and Literature, University of South China, Hengyang, Hunan 421001, China

Abstract: The Technological Pedagogical Content Knowledge (TPACK) framework has delineated developmental trajectories for teachers' knowledge structures in the information age while establishing a theoretical foundation for teacher education. From a global perspective, research on teachers' TPACK is experiencing prolific growth, yet systematic syntheses of its current status, research hot spots, and emerging trends remain imperative. This study reveals three key findings: (1) Global research on teachers' TPACK demonstrates a sustained upward trajectory; (2) Current scholarly emphasis concentrates on information technology integration and digital competencies, educational ecosystems and professional development, and subject-specific pedagogy and methodological innovations; (3) Future investigations are projected to prioritize learning strategy optimization and transformative digital technologies.

Keywords: TPACK, CiteSpace, Visualization Analysis.

1. Introduction

Since Koehler and Mishra introduced the Technological Pedagogical Content Knowledge (TPACK), its application in teacher education has sparked extensive discussions within the academic community. This theory emphasizes that in the information age, teachers' knowledge structure should encompass seven key components: Technological Knowledge (TK), Content Knowledge (CK), and Pedagogical Knowledge (PK), as well as their intersections forming Pedagogical Content Knowledge (PCK), Technological Pedagogical Knowledge (TPK), Technological Content Knowledge (TCK), and the fully integrated Technological Pedagogical Content Knowledge (TPACK). As one of the significant research directions in the field of international educational technology, the TPACK theory has continued to attract scholars' attention. Alchambault [1] conducted a factorial analysis to investigate the nature of TPACK and tested the validity of the TPACK model. Chai and other scholars [2] examined pre-service teachers' perceptions of TPACK in ICT courses using a questionnaire adapted from Schmidt. Scholars such as Joo [3] investigated the structural relationships among TPACK, teachers' self-efficacy, perceived ease of use, and perceived usefulness of intending to use technology among pre-service teachers based on the Technology Acceptance Model.

Current research primarily focuses on the theoretical construction, influencing factors, and cultivation strategies of TPACK, and has achieved fruitful results. However, due to the broad range of fields involved and the relatively short development time, research in this area exhibits a degree of dispersion and has yet to form a comprehensive research system. With the aid of CiteSpace software, this paper conducts a visual analysis of the distribution of relevant literature, highly cited literature, and co-occurrence of keywords in TPACK research on teachers from a global perspective. The aim is to objectively present the development trends and research hotspots of TPACK research on teachers in a global context, and to provide certain references and insights for future research in the field of TPACK.

2. Materials and Methods

2.1. Data Collection

In this study, data analysis was performed on Social Sciences Citation Index (SSCI) journals collected from the Web of Science (WOS) database. Considering that the first closely related paper on teachers' TPACK research was published in 2010, the topic of "TPACK" and "Teacher" were searched with a retrieval span from 2010 to September 9th, 2024. A total of 797 records were retrieved and after removed irrelevant entries, the final number of valid documents related to teachers' TPACK from a global perspective was determined to be 661.

2.2. Research Methods

This study employed bibliometric analysis and utilized the bibliometric software CiteSpace 6.1.R6 to create knowledge maps of papers related to teachers' TPACK published in international core journals. Microsoft Excel was used to organize data and create visual representations. By adopting data processing methods in CiteSpace such as Author, Institution, and Keywords, the study analyzed the current development status and hotspots in the field of teachers' TPACK research from a global perspective. The time span was set from 2010 to 2024, with a time slicing of one year. The remaining data parameters were set to the system's default values.

3. Results

3.1. Publication Output

The number of international publications on the theoretical research of teachers' TPACK exhibits an overall growth trend with certain fluctuations (see Figure 1). It can be broadly divided into three phases. In the early phase (2010-2013), the number of publications gradually increased from 9 to 19, showing a steady upward trend. During the mid-phase (2014-2018), there were significant fluctuations in the number of publications, peaking at 43 in 2014 before declining slightly to 38 in 2018. In the later phase (2019-2024), the number of

publications continued to fluctuate but maintained an overall upward trend. Between 2019 and 2021, there was a rapid increase, reaching 75 publications in 2021. In 2022, it declined slightly to 68. Since only papers published prior to the research date were included, it is anticipated that the number of publications in 2024 will still be relatively high.

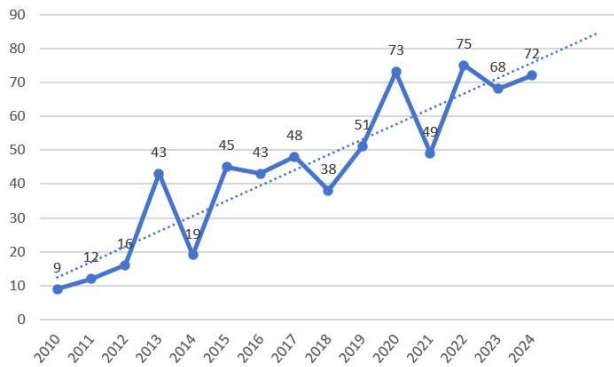


Fig.1 Distribution of publications by years

3.2. Countries / Regions

The degree of contribution and hotspots in the field of teacher leadership research by various countries can be reflected and understood through their statistical data. As shown in the table, China is showing a vigorous development trend in the field of teachers' TPACK research. Considering the number of publications from both mainland China and Taiwan, China ranks first in terms of publication volume. The other top ten countries or regions in terms of international publications are the United States, Turkey, Australia, Germany, Singapore, the Netherlands, Belgium, and England. This indicates that Chinese scholars are active in the field of theoretical research on teachers' TPACK and actively voice their opinions on the international academic stage. Scholars from both China and the United States attach great importance to the field of theoretical research on teachers' TPACK, followed by scholars from Turkey, Australia, Germany, and others, who, together with scholars from other countries, are driving the further development of theoretical

research on teachers' TPACK.

Table 1. Top 10 productive countries/ regions (2010-2024)

Rank	Countries/ Regions	Publication	Rank	Countries/ Regions	Publication
1	USA	165	6	Germany	38
2	China	108	7	Singapore	37
3	Turkey	84	8	Netherlands	27
4	Taiwan	75	9	Belgium	18
5	Australia	49	10	England	18

3.3. Authors

A statistical analysis of authors' publications reveals that a total of 1,487 scholars have published papers on the theoretical research direction of teachers' TPACK in international core journals from 2010 to 2024. Among them, the vast majority of scholars have only published one article, indicating that expertise in the field of teachers' TPACK theoretical research is concentrated among a small number of scholars, such as Chai Ching Sing, Koh Joyce Hwee Ling, Tsai Chin-Chung, Liang Jyh-Chong, and Baran Evrim. Table 2 lists the specific information of the top ten authors in terms of publication volume in the field of teachers' TPACK research. From the perspective of the starting year of publication, seven authors first published their work between 2010 and 2013, contributing a total of 96 articles; two authors first published between 2014 and 2018, with a cumulative publication volume of 13 articles; and one author first published between 2019 and 2024, with five articles. Due to the impact of the pandemic and the prevalence of online teaching, the number of research publications by scholars from various countries in the field of teachers' TPACK has decreased. However, as shown in the table, scholars from Hong Kong, China, such as Chai Ching Sing, and scholars from Taiwan, China, including Tsai Chin-Chung and Liang Jyh-Chong, have made outstanding contributions to the development of teachers' TPACK research. Furthermore, scholars from Hong Kong and Taiwan are slightly ahead of mainland Chinese scholars in the field of teachers' TPACK theoretical research.

Table 2. Top 10 productive authors (2010-2024)

Rank	Authors	Countries/ Regions	Publications	Beginning Time
1	Chai Ching Sing	Hongkong	32	2010
2	Koh Joyce Hwee Ling	New Zealand	21	2010
3	Tsai Chin-Chung	Taiwan	14	2010
4	Liang Jyh-Chong	Taiwan	9	2013
5	Baran Evrim	USA	8	2017
6	Tondeur Jo	Belgium	8	2011
7	Blonder Ron	Israel	6	2012
8	Voogt Joke	Netherlands	6	2013
9	Backfisch Iris	Germany	5	2017
10	Chai Ching-Sing	Hongkong	5	2021

3.4. Co-Citation

Co-citation analysis is the most notable feature of CiteSpace. Co-citation refers to the relationship between two documents that are cited simultaneously in the reference list of a third citing document. The process of mining co-citation relationships within a dataset of literature can be regarded as

co-citation analysis. Highly cited documents are not only classic references that are widely recognized and cited within the research field but also constitute the knowledge base of that field[4].

Table 3. Top 10 highly cited reference

Rank	Title	Author	Year	Count	Centrality
1	Those Who Understand: Knowledge Growth in Teaching	Shulman LS	2019	300	0.2
2	Technological Pedagogical Content Knowledge - A Review of the Literature	Voogt J	2013	61	0.03
3	A Review of Technological Pedagogical Content Knowledge	Chai CS	2013	50	0.07
4	Technological Pedagogical Content Knowledge (TPACK): The Development and Validation of an Assessment Instrument for Preservice Teachers	Schmidt DA	2009	50	0
5	Exploring Teachers' Perceived Self Efficacy and Technological Pedagogical Content Knowledge with Respect to Educational Use of the World Wide Web	Lee MH	2010	49	0.07
6	Epistemological and Methodological Issues for the Conceptualization, Development, and Assessment of ICT-TPCK: Advances in Technological Pedagogical Content Knowledge (TPCK)	Angeli C	2009	47	0.01
7	Theoretical Considerations for Understanding Technological Pedagogical Content Knowledge (TPACK)	Graham CR	2011	45	0.01
8	Considering Contextual Knowledge: The TPACK Diagram Gets an Upgrade	Mishra P	2019	41	0.1
9	Revisiting Technological Pedagogical Content Knowledge: Exploring the TPACK Framework	Archambault LM	2010	39	0.01
10	Diagramming TPACK in Practice: Using an Elaborated Model of the TPACK Framework to Analyze and Depict Teacher Knowledge	Cox S	2009	37	0.02

By combining citation frequency and centrality, we have selected the top ten classic articles with the highest citation rates in TPACK research on teachers over the past two decades (see Table 3). It can be observed that these articles primarily focus on refining the theoretical concepts of TPACK, constructing frameworks, and developing assessment tools. Among them, *“Those Who Understand: Knowledge Growth in Teaching”* by Lee S. Shulman has the highest citation frequency and a centrality of 0.2. To investigate teachers' professional knowledge, Shulman and his colleagues initiated the *“Knowledge Growth in Teaching”* project in the mid-1980s. This article presents the findings of the project, which indicate that in addition to content knowledge, there is a need for “pedagogical content knowledge” and contextual knowledge (curriculum knowledge). Therefore, beyond knowledge, good teaching also requires understanding. Shulman [5] emphasizes teachers' comprehension, reasoning, and transformation, arguing that how teachers convert their subject matter knowledge into forms that are easily understandable for students affects their teaching quality. Teachers must know how to transform their disciplinary knowledge into a form that students can comprehend for their teaching to be successful. Guided by this very concept, Shulman defined seven types of knowledge that constitute the foundational knowledge for teaching, and this literature has become a groundbreaking work in the theory of TPACK for teachers, laying a solid foundation for subsequent research. Scholars such as Voogt J [6] conducted a systematic literature review of articles on TPACK published between 2005 and 2011, investigating the theoretical foundations and practical applications of TPACK. The study found that there are different understandings of TPACK and technological knowledge. The influence of these differing viewpoints has impacted how TPACK is measured, and active participation in (re)designing and implementing technology-enhanced curricula has proven to be a promising strategy for (student) teachers to develop their TPACK. Lee MH [7] provided a framework to understand teachers' Technological Pedagogical Content Knowledge - Web (TPCK-W),

integrating web technology into teachers' instructional practices, and developed a new survey, namely the TPCK-W Survey, to explore teachers' self-efficacy in TPCK-W and assess their attitudes towards online teaching. The results indicated a correlation between self-efficacy and positive attitudes towards online teaching. Older, more experienced teachers demonstrated lower self-efficacy in TPCK. Angeli C [8] introduced ICT-TPCK as a subset of TPCK, describing it as the knowledge of tools and their functions, pedagogy, content, and learners, to understand how to leverage technology in ways that demonstrate its added value, thereby more effectively transforming and teaching specific topics that are difficult for learners to understand or for teachers to represent. The theoretical model proposed in the article can have a positive impact on the development of ICT-TPCK. Archambault LM [9] examined the nature of TPACK by utilizing factor analysis and measured the responses of 596 online teachers from various parts of the United States through a questionnaire survey. The study investigated the effectiveness of the TPACK framework in practice and found that it was difficult to differentiate between the various domains.

3.5. Keywords

To explore the hot topics in the field of teachers' TPACK theoretical research, this study first used CiteSpace software to create a co-occurrence map of keywords. After merging synonymous keyword nodes in the map, cluster analysis was conducted to obtain a knowledge map of keyword clusters for teachers' TPACK theoretical research (see Figure 2). The map modularity value is 0.7584 (>0.3), and the average silhouette value is 0.9086 (>0.7). These two indicators indicate that the clustering structure of the map is significant and the clustering results are convincing. Figure 2 shows 13 clusters in the theoretical research on teachers' TPACK, namely virtual reality, educational technology, school, middle school, mathematics education, pre-service teachers, competencies, technological pedagogical content knowledge (TPACK), pedagogical issues, online teaching, factor analysis, data science, and 21st-century digital skills. Further analysis

reveals that these keyword clusters reflect the research focus of scholars worldwide in the field of teachers' TPACK theoretical research, which mainly concentrates on information technology and digital skills, teaching environments and teacher development, and subject teaching and research methods. Below, specific literature information will be combined to elaborate on the international hot topics in TPACK research from these three aspects.

(1) Information Technology and Digital Skills

Teaching is a dynamic process, and teachers should adopt new methods and technologies. The development of computer technology has set higher requirements for teachers' ability to integrate technology. Furthermore, the widespread outbreak of pandemics worldwide has compelled education to seek different platforms and new technologies, creating opportunities for the application of virtual reality (VR). Jiang MYC [10], based on a VR-supported L1 Chinese writing course, collected and analyzed a set of VR courseware, lesson plans, and student assignments developed by Chinese teachers in Hong Kong. They found that teachers were able to utilize VR to immerse students in real-life situations, fostering students' autonomous learning abilities and their understanding of the nuanced socio-emotional aspects of L1 Chinese writing. Chen Mengyuan and Chai Ching-sing [11] designed a writing class supported by Spherical Video Virtual Reality (SVVR). The research results indicate that SVVR can be used to enrich students' compositions and enhance their descriptive writing skills. The use of technology primarily improves student learning outcomes by enhancing classroom learning efficiency. However, most teachers still lack technical knowledge in teaching situations. Consequently, researchers have conducted studies on teachers' 21st-century digital skills within the framework of TPACK theory. For example, Ong Quinie Kooi Loo and Annamalai Nagaletchimee [12] investigated the development of Technological Pedagogical Content Knowledge for 21st-century Learning Skills (TPACK21cls) in the planning, delivery, and experiential courses of English as a Second Language (ESL) teaching programs at the Malaysian Institute of Teacher Education (ITE). They found a lack of TPACK21cls, while content knowledge and pedagogical content knowledge were emphasized in the planned courses. This has significant implications for the teaching and learning of information and communication technology in schools and ITEs.

(2) Teaching Environment and Teachers' development

The research on teaching environments and teacher development encompasses keywords such as online and offline teaching, and the development of pre-service teachers or teacher candidates. Leveraging technology for teaching is a pillar of online higher education pedagogy. However, it is currently unclear whether and how online teaching practices influence the development of students' soft skills. Bouhout Najib [13] have found that TPACK is a significant factor in developing students' soft skills in online higher education, further emphasizing the importance of student-centered, active, and emotionally engaging teaching approaches. New teachers should possess the ability to integrate and innovate teaching curricula and technological designs. An important issue is how to integrate technology into the content knowledge of pre-service teachers. Many scholars have conducted research on how to integrate technology into content knowledge and how to improve the level of integration. Jang Syh-Jong and Chen Kuan-Chung [14]

designed a transformational model and an online system to reorganize teacher education courses. This model helps in-service teachers develop technological pedagogy and integrate disciplinary knowledge into strategies for science courses, further enhancing their TPACK capabilities. Camino Bueno-Alastuey M [15] has found that remote collaboration facilitates the collaboration of various knowledge and abilities within TPACK, allowing teachers to direct students' attention to their own TPACK. Valtonen Teemu [16] has provided a new perspective on researching TPACK by allowing pre-service teachers to self-evaluate their TPACK areas that are both challenging and confident. They found that for these prospective teachers, pedagogical knowledge plays the most crucial role, and generating concrete pedagogical knowledge can address some TPACK issues in teacher education.

(3) Subject Teaching and Research Methods

Centering around subject teaching and research methods, researchers focus on methods for integrating technology into specific subject teaching, studying teaching effectiveness, and conducting scientific research on educational issues using methods such as factor analysis. Keywords include mathematics education, knowledge and abilities, and factor analysis. Chai Ching Sing [17] found that surveys measuring teachers' STEM self-efficacy from a TPACK perspective have adequate validity and reliability. Structural equation modeling indicates that teachers' integration of technology into science, mathematics, and engineering subjects enhances their teaching effectiveness. Scholars such as Patahuddin Sitti Maesuri [18] conducted an experiment in a middle school mathematics classroom in an early education setting in Indonesia, where web-based teaching resources were used to support students' understanding of fractions. The research showed that the combination of instructional stance and technology choices significantly affected the visibility of other TPACK concepts. In future teaching, teachers should carefully plan before using web resources and utilize key information in the process of developing and assessing their TPACK. The development of the internet has transformed teachers' teaching and learning models. Ning Yimin [19] explored the relationships among the knowledge elements of teachers' AI-TPACK through exploratory factor analysis and confirmatory factor analysis. The study found that the impact of core knowledge elements (PK, CK, and AI-TK) on AI-TPACK is indirect, mediated by composite knowledge elements (PCK, AI-TCK, and AI-TPK), with each element playing a unique role. These studies are of great significance for the sustainable development of teachers in the era of artificial intelligence.

Frontier topics can be viewed as scientific issues or special topics discussed in a set of literature over a certain period of time, with emergent keywords serving as the knowledge foundation. As shown in the keyword emergence map (see Figure 3), early research (2010-2013) focused on integrating technology, Technological Pedagogical Content Knowledge (TPACK), and pedagogical issues, indicating that with the continuous development of information technology, the education field has gradually emphasized the effective integration of digital technology with traditional teaching content to enhance teaching effectiveness. The TPACK framework has emerged as a crucial theoretical framework for guiding teachers to integrate technology into teaching practice. During the mid-period (2014-2018), research topics shifted to the exploration of information and communication

technology (ICT), TPACK theoretical models and frameworks, and their applications in specific disciplines, reflecting researchers' dedication to establishing systematic theoretical frameworks to better understand and improve educational practice. These frameworks and models not only help scholars explain educational phenomena but also provide theoretical support for actual teaching, with keywords including framework, ICT, model, and mathematics. Recent research hotspots concentrate on learning strategies and digital technology. With the rapid development of digital technology, teachers need to explore new learning strategies

to enhance their TPACK capabilities, and future research will also focus on digital technology and learning strategies. Overall, future research topics will not only prioritize the application of digital technology, especially in the integration of teaching content with technology, leveraging frameworks such as TPACK to help teachers more effectively use technology to improve teaching effectiveness, but will also broaden educational focus from mere academic achievement to students' psychological and social growth, emphasizing the creation of a learning environment that supports students' comprehensive development in a multicultural context.

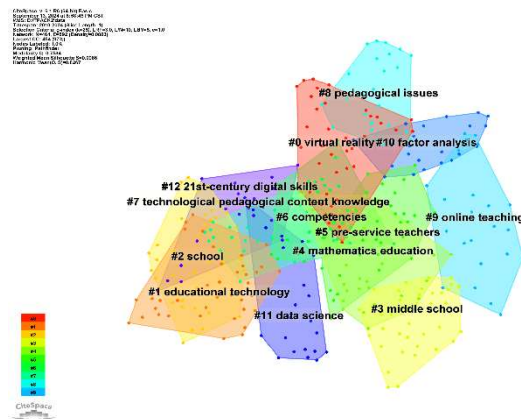


Fig.2 Cluster map of keywords

Keywords	Year	Strength	Begin	End	2010 - 2024
integrating technology	2010	4.95	2010	2014	[Red bar]
technological pedagogical content knowledge	2010	3.1	2010	2013	[Red bar]
pedagogical issue	2010	2.83	2010	2012	[Red bar]
conceptualization	2012	2.87	2012	2015	[Red bar]
framework	2010	3.7	2013	2014	[Red bar]
ict	2010	3.05	2013	2015	[Red bar]
model	2010	2.78	2013	2015	[Red bar]
school	2013	2.63	2013	2018	[Red bar]
growth	2013	3.98	2014	2017	[Red bar]
respect	2015	5.71	2015	2020	[Red bar]
mathematics	2010	2.69	2016	2017	[Red bar]
construction	2018	2.66	2018	2019	[Red bar]
teacher educator	2019	2.57	2019	2021	[Red bar]
learning strategy	2022	3.3	2022	2024	[Red bar]
digital technology	2022	3.24	2022	2024	[Red bar]

Fig.3 Top 15 keywords with the strongest citation bursts

4. Conclusion

Through multi-dimensional visual analysis of annual publication volume, research institutions, authors, and keywords, the following conclusions can be drawn.

General publication trend in the area of global teacher TPACK research: From 2010 to 2024, international research on TPACK has shown an overall upward trend, reaching a climax in the past four years. This indicates that TPACK research among teachers is receiving increasing attention from scholars worldwide.

The countries/ regions and cited references contributing most to the global teacher TPACK research: The top ten countries or regions in terms of international publications are China, USA, Turkey, Australia, Germany, Singapore, the Netherlands, Belgium, and England. Among them, teacher education universities in Hong Kong and Taiwan regions of China play a pivotal role in research on teachers' TPACK. In the past decade, highly cited reference has concentrated in the field of education. The most

frequently cited publication is "Those Who Understand: Knowledge Growth in Teaching" by Shulman LS, which is a groundbreaking work in the theory of teachers' TPACK and has laid a solid foundation for subsequent research.

The hotspots of global teacher TPACK research: A total of 13 clusters have been formed, and through analysis, it can be seen that research hotspots focus on information technology and digital skills, teaching environment and teacher development, subject teaching and research methods, etc. With the rapid development of artificial intelligence, the requirements for teachers' ability to integrate technology are becoming increasingly high, and future research will center around "learning strategies" and "digital technology."

In summary, through visual analysis and a review of key literature in the field of TPACK research over the past decade, it can be found that research in this area has gradually deepened, the scope of research has continuously expanded, and considerable research achievements have been made. However, there are still some issues that deserve further in-depth exploration and discussion.

Firstly, teaching research based on the TPACK framework has mostly concentrated on subjects such as mathematics, information technology, English, and chemistry, with relatively little attention paid to subjects like Chinese, geography, and politics. Therefore, future research should focus on the diversity of disciplines within TPACK research, thereby expanding the application scope of TPACK theory across different subjects. Secondly, there is relatively little research combining it with other components of teachers' knowledge structures, such as their cultural backgrounds, personal beliefs, and teaching perspectives. Thus, future research needs to integrate these perspectives comprehensively in order to better apply TPACK into teacher education systems. Lastly, with the development of technology, research on the TPACK framework should also be in a state of dynamic change to accommodate emerging teaching technologies.

Acknowledgments

This work was supported by grants from Higher Education Reform Research Project of Hunan Province (Grant No.202401000865), Industry-Academia-Research Collaborative Talent Development Project of the Ministry of Education (Grant No. 230806194253615), and Degree and Graduate Education Reform Research Project of University of South China (Grant No. 2023JG024).

References

- [1] Archambault L M, Barnett J H. Revisiting technological pedagogical content knowledge: Exploring the TPACK framework[J]. *Computers & Education*, 2010, 55(4): 1656-1662.
- [2] Chai C S, Koh J H L, Tsai C C. Facilitating preservice teachers' development of technological, pedagogical, and content knowledge (TPACK)[J]. *Journal of Educational Technology & Society*, 2010, 13(4): 63-73.
- [3] Joo Y J, Park S, Lim E. Factors influencing preservice teachers' intention to use technology: TPACK, teacher self-efficacy, and technology acceptance model[J]. *Journal of Educational Technology & Society*, 2018, 21(3): 48-59.
- [4] Li J, Chen C. *CiteSpace: Text Mining and Visualization in Science and Technology*[M]. Beijing: Capital University of Economics and Business Press, 2017.
- [5] Shulman L S. Those who understand: knowledge growth in teaching [J]. *Educational Researcher*, 1986, 15(2): 4-14.
- [6] Voogt J, Fisser P, Pareja Roblin N, et al. Technological pedagogical content knowledge—a review of the literature[J]. *Journal of computer assisted learning*, 2013, 29(2): 109-121.
- [7] Lee M H, Tsai C C. Exploring teachers' perceived self efficacy and technological pedagogical content knowledge with respect to educational use of the World Wide Web[J]. *Instructional Science*, 2010, 38: 1-21.
- [8] Angeli C, Valanides N. Epistemological and methodological issues for the conceptualization, development, and assessment of ICT-TPCK: Advances in technological pedagogical content knowledge (TPCK)[J]. *Computers & Education*, 2009, 52(1): 154-168.
- [9] Archambault L M, Barnett J H. Revisiting technological pedagogical content knowledge: Exploring the TPACK framework[J]. *Computers & Education*, 2010, 55(4): 1656-1662.
- [10] Jiang M Y C, Jong M S Y, Chai C S. Understanding teachers' multimodal TPACK literacies for supporting VR-based self-directed learning of L1 writing[J]. *Educational Technology & Society*, 2024, 27(3): 303-317.
- [11] Chen M, Chai C, Jong M S Y. Actualization of teaching conceptions in lesson design: how teaching conceptions shape TPACK regarding spherical video-based virtual reality-supported writing instruction[J]. *Educational technology research and development*, 2023, 71(6): 2321-2344.
- [12] Ong Q K L, Annamalai N. Technological pedagogical content knowledge for twenty-first century learning skills: The game changer for teachers of industrial revolution 5.0[J]. *Education and Information Technologies*, 2024, 29(2): 1939-1980.
- [13] Bouhout N, Askitou A, Es-soufi K. TPACK for soft skills in online higher education: A factor-based PLS-SEM analysis of the mediating role of care[J]. *Education and Information Technologies*, 2024: 1-21.
- [14] Jang S J, Chen K C. From PCK to TPACK: Developing a transformative model for pre-service science teachers[J]. *Journal of Science Education and Technology*, 2010, 19: 553-564.
- [15] Bueno-Alastuey M C, Villarreal I, García Esteban S. Can telecollaboration contribute to the TPACK development of pre-service teachers?[J]. *Technology, Pedagogy and Education*, 2018, 27(3): 367-380.
- [16] Valtonen T, Leppänen U, Hyypiä M, et al. Fresh perspectives on TPACK: pre-service teachers' own appraisal of their challenging and confident TPACK areas[J]. *Education and Information Technologies*, 2020, 25(4): 2823-2842.
- [17] Chai C S, Jong M, Yin H, et al. Validating and modelling teachers' technological pedagogical content knowledge for integrative science, technology, engineering and Mathematics education[J]. *Journal of Educational Technology & Society*, 2019, 22(3): 61-73.
- [18] Patahuddin S M, Lowrie T, Dalgarno B. Analysing mathematics teachers' TPACK through observation of practice[J]. *The Asia-Pacific Education Researcher*, 2016, 25: 863-872.
- [19] Ning Y, Zhang C, Xu B, et al. Teachers' AI-TPACK: Exploring the relationship between knowledge elements[J]. *Sustainability*, 2024, 16(3): 978.