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Review Article

Technological pedagogical content knowledge in science education: A scientometric review

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ABSTRACT

This study presents one of the first scientometric reviews of technological pedagogical content knowledge (TPACK) in science education. The review highlights how teachers' digital pedagogical knowledge has been conceptualised and evolved to support learner-content, learner-teacher, and learner-technology interaction in science education. The analysis drew on 564 bibliographic records from the Web of Science from 2014 to 2024. Quantitative methods were applied to capture publication growth, citation impact, contributions from countries, institutions, journals and authors, and thematic development. Data analysis included network analysis, polynomial regression, least squares trend analysis, and Chi-square tests. Bradford's and Lotka's laws were applied to assess journal and author productivity. Science mapping tools supported visualization, including VOSviewer, Biblioshiny, and the Bibliometrix R package. Advanced statistical analyses were performed using the statistical package for the social sciences. The results show accelerated growth in TPACK publications after 2018, with output peaking between 2020 and 2022 as pandemic-driven demands increased the use of educational technologies. China, the United States, and Turkey emerged as the leading contributors, while Nanyang Technological University and the Chinese University of Hong Kong dominated institutional output. Chai Ching Sing was found to be the most prolific author. Author productivity revealed that TPACK scholarship in science education is dominated by one-time contributors supported by a small core of active scholars. Thematic evolution reveals a shift from knowledge integration toward teacher education and professional development, with recent expansion into mathematics and science education.

Keywords: TPACK, science education, scientometrics, science mapping, citation analysis, thematic evolution

INTRODUCTION

Science education is widely recognized as one of the most demanding domains of teaching. This is because it requires teachers to draw on extensive disciplinary and pedagogical knowledge to make abstract and often invisible phenomena accessible to learners (Abd-El-Khalick, 2013; García-Carmona, 2025; Hofstein & Lunetta, 2004). The stakes are heightened by the rise of artificial intelligence (AI). Teachers must now consider AI not merely as a supportive tool but as an active co-creator of knowledge alongside learners (Harari, 2017; Mishra et al., 2025). Nonetheless, while the rise of AI and other innovative technologies in the classroom adds a layer of complexity to the knowledge teachers require, these innovations simultaneously open unprecedented possibilities to model scientific phenomena, visualize the invisible, and connect learners with authentic scenarios (Hwang, 2020; Ng et al., 2025). However, such affordances rarely yield deeper understanding because they depend on intentional pedagogical design. Without robust teacher knowledge that integrates content, pedagogy, and technology, the transformative potential of these AI innovations risks being reduced to superficial use.

In this shifting terrain, technological pedagogical content knowledge (TPACK) continues to gain salience as a form of evolving teacher knowledge attuned to the complexities of teaching with emerging technology (Mishra et al., 2025; Petko et al., 2025). Building on Shulman's (1986) seminal notion of pedagogical content knowledge (PCK), TPACK emphasizes the dynamic and multi-dimensional interplay of disciplinary, pedagogical, and technological domains that teachers must mobilize to design meaningful learning (Mishra & Koehler, 2006; Petko et al., 2025). In science education, where global priorities emphasize scientific literacy, inquiry, and problem-solving, TPACK has proven especially valuable in supporting teacher preparation and continuous professional development. Over the past decade, scholarship on TPACK in science education has expanded considerably, shedding light on how teachers appropriate integrated forms of content, pedagogical, and technological knowledge to prepare learners for participation in knowledge-intensive societies. With the rapid rise of AI and data-driven technologies, TPACK is evolving to accommodate new demands, underscoring its adaptability as teachers reconfigure their knowledge to integrate these innovations meaningfully. Yet, despite this momentum, limited systematic mapping has been conducted to trace how these evolving themes intersect with established strands of TPACK scholarship. In this direction, scientometric approaches have emerged as powerful means to provide a panoramic view of the literature. These methods capture both the structural patterns and the semantic content, while also helping to identify key gaps and future directions.

Scientometrics

Broadly defined, scientometrics is the quantitative study of science and its communication. It includes analyzing geographic or institutional patterns of scientific activity, tracking knowledge evolution over time, and identifying emerging research areas (Ivancheva, 2008). Scientometrics is closely related to bibliometrics and informetrics, which examine the dynamics of disciplines through their literature (Hood & Wilson, 2001) and provide quantitative insights into trends, growth, and interrelationships in science (Kastrin & Hristovski, 2021). The term originated from Nalimov and Mulchenko's (1969) Russian monograph *Naukometriya,* which remained largely unknown until the launch of the journal *Scientometrics* in 1978 (Garfield, 2009). Since its introduction, it has systematically studied scientific growth, structure, productivity, and interconnections (Mingers & Leydesdorff, 2015). In the context of TPACK research in science education, applying scientometrics offers a novel contribution by employing scientometric methods to systematically analyze the field's published literature. Mapping trends, key contributors, and conceptual trajectories reveals the intellectual structure of the discipline while identifying emerging themes and overlooked gaps.

This scientometric review of TPACK research in science education seeks to advance understanding of its evolution through five objectives:

1. To map the growth trajectory of TPACK research in science education through publication and citation trends.
2. To identify leading countries and institutions driving the field and evaluate their influence.
3. To recognize prolific authors and key journals that shape the visibility of TPACK scholarship.
4. To trace the intellectual foundations and citation impact of seminal works defining TPACK research.
5. To analyze keyword patterns and thematic evolution to understand shifting trends in TPACK research in science education.

LITERATURE SYNTHESIS

In recent years, scientometrics has increasingly been applied across diverse scientific fields. However, despite its growing application, the use of scientometrics in educational research remains limited, and scientometric studies specifically addressing TPACK are particularly scarce. To date, only one notable scientometric study exists, Yalçın and Yayla (2016). Given that this study is now nearly a decade old, the field lacks up-to-date scientometric insights. This scarcity compels us to draw on related bibliometric studies and other analyses of TPACK research.

Firstly, Yalçın and Yayla (2016) conducted a scientometric analysis of 543 TPACK-related publications from Web of Science (WoS) and Scopus. Using author co-citation and document co-citation analyses, the study identified dominant contributions from countries such as the United States, Canada, and Brazil, with leading institutions including Purdue University and the University of California. Influential journals included *Computers & Education* and *Educational Technology Research and Development*. The thematic focus of the publications centered on teacher education, technology integration, and curriculum development. This study highlighted the research's geographical and institutional distribution and the foundational knowledge base shaping the field.

Building on this, Amiruddin et al.'s (2024) bibliometric study analyzed TPACK research in science education spanning 2013 to 2023 using Scopus data, visualized through R and VOSviewer. The study reported a rising publication trend and identified prominent authors, including Fischer, Thomas, and Huwer. In addition, the study identified leading journals such as the *Journal of Research in Science Teaching* and the *International Journal of Science Education*. The analysis revealed key themes emphasizing technology integration into teaching practices and the impact of TPACK on enhancing science education outcomes. This work confirmed the growing scholarly attention to TPACK, particularly concerning STEM teaching contexts, and illustrated the increasing international collaboration in the field.

Karampelas (2023) provided further insights by examining the intersection of TPACK and science, technology, engineering, arts, and mathematics (STEAM) education. The bibliometric analysis of 2608 publications from 2007 to 2022 revealed a strong interdisciplinary orientation, underscoring technology integration with broader educational frameworks. This research emphasized TPACK's relevance in designing effective teaching strategies within STEAM education, thereby expanding the conceptual reach of TPACK beyond traditional subject-specific studies.

Similarly, Putri et al.'s (2022) bibliometric research explored TPACK research in science education from 2012 to 2021 using 910 Scopus-indexed publications. The study reported a fluctuating pattern of publication trends during the period. The research further mapped prolific authors, institutions, and collaboration networks, illustrating that co-authorship is dominated by single-country authorship. The study reinforced that TPACK research is increasingly globalized yet concentrated within certain high-output countries and institutions.

Lastly, Lee et al.'s (2022) bibliometric review examined 700 TPACK publications from 2011 to 2020, focusing on publication trends and thematic developments. Results showed that the United States, Turkey, and Australia lead in publication output, with American institutions producing the highest number of articles, followed by Asian institutions. Interestingly, the most prolific authors are predominantly Asian, followed by American scholars. Highly cited articles focus on PCK, teacher education, teaching skills, and pedagogy, indicating a shift from theoretical conceptualization toward practical strategies for technology-assisted teaching. Publication in educational technology journals dominates, and citations peaked in 2013, with a steady rise in articles since 2016.

Gaps and Justification for the Study

TPACK research is expanding in volume and scope, emphasizing technology integration, teacher education, and interdisciplinary approaches. However, scientometric investigations remain scarce. Only Yalçın and Yayla (2016) conducted such an analysis nearly a decade ago. While informative, existing systematic reviews and bibliometric studies provide a limited view of the field's intellectual structure and collaboration patterns. As one of the first scientometric analyses, this study addresses these gaps by systematically mapping publication trends, influential contributors, co-authorship networks, and emerging themes. To guide future studies, the current study aims to offer a holistic scientometric understanding of TPACK research in science education.

METHODOLOGY

Science mapping was employed to analyze TPACK research in science education as shown in **Figure 1**. Science mapping refers to a broad set of techniques for analyzing and visualizing a research domain to allow scholars to trace its intellectual structure, monitor thematic developments, and reveal patterns of knowledge relationships (Börner et al., 2003; Cobo et al., 2011). Science mapping studies typically apply bibliometric or scientometric techniques. Accordingly, we adopted a scientometric approach for this study. Following

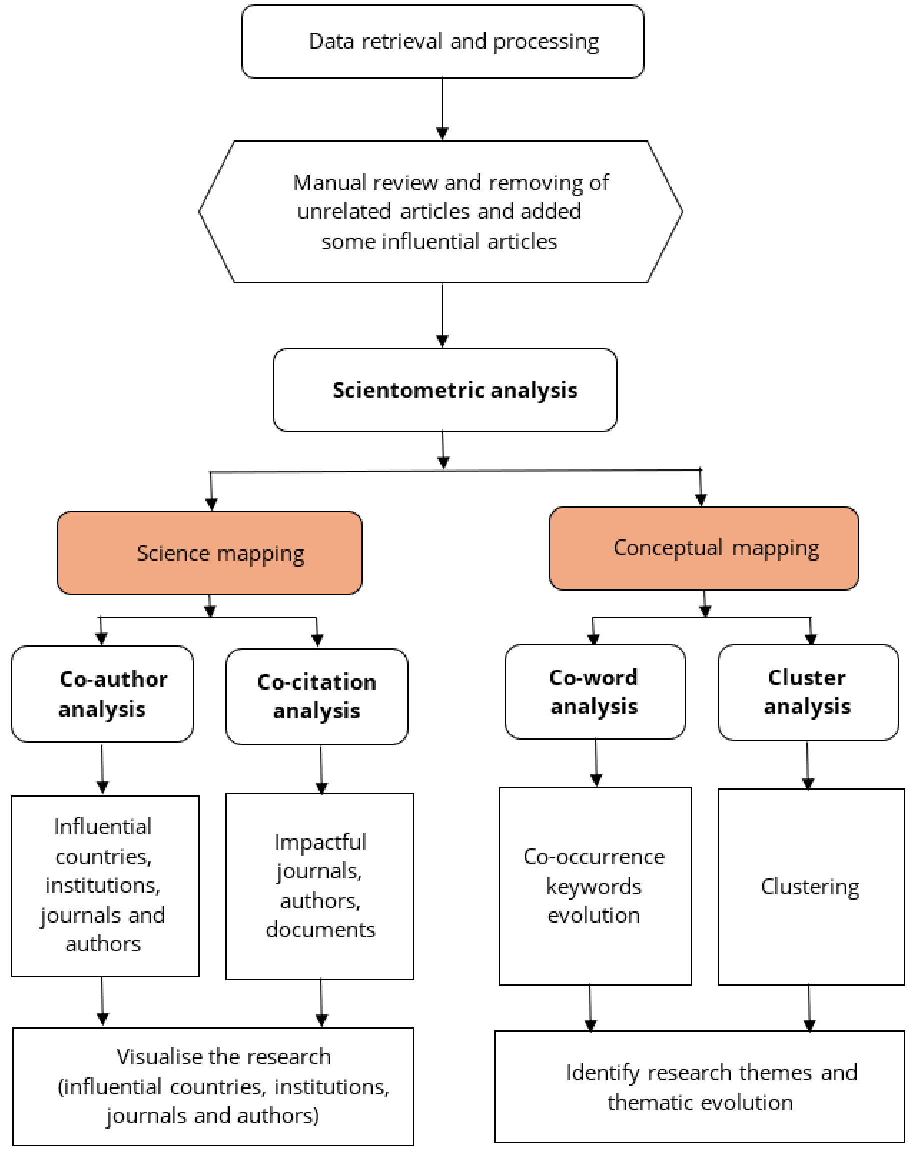

Figure 1. Methodology flow (developed by the author based on the study design)

established best practices, our methodology was designed to include four phases which are selection of science mapping tools, data collection and processing, data visualization, and presentation and interpretation of findings.

Science Mapping Tools Selection

Multiple complementary scientometric tools were used to ensure a rigorous and multi-dimensional analysis of publication patterns, intellectual structures, and thematic developments. The Bibliometrix R-package (Aria & Cuccurullo, 2017) was selected as the core analytical tool due to its capacity to perform comprehensive bibliometric analyses, including performance indicators, science mapping, and thematic evolution. The use of the Bibliometrix R-package in this study is consistent with prior TPACK-focused research, where it has been employed to conduct performance analysis, science mapping, and thematic exploration of the field (e.g., Lee et al., 2022; Prasetya & Irwanto, 2025; Simangunsong et al., 2023). To further examine the intellectual and collaborative structure of the field, VOSviewer (van Eck & Waltman, 2010) was used for network visualization because of its strength in constructing and interpreting co-authorship, co-citation, and keyword co-occurrence networks. This enabled the identification of collaborative patterns and the intellectual structure of the field, an approach widely adopted in TPACK and educational technology reviews to map influential authors, sources, and knowledge clusters (e.g., Helingo & Nurpahmi, 2024; Suprapto et al., 2021).

Table 1. Key information of TPACK in education

	Description	Results
Main information about the data	Timespan	2014:2024
	Sources (journals)	213
	Documents	564
	AGR (%)	14.9
	Document average age	4.7
	Average citations per document	32.09
Document contents	Keywords plus (ID)	522
	Author's keywords (DE)	1,366
Authors	Authors	1,516
	Authors of single-authored docs	99
Authors collaboration	Single-authored docs	111
	Co-authors per document	2.89
	International co-authorships (%)	19.94
Document types	Article	564

In addition, the statistical package for the social sciences (SPSS) was employed to extend the analysis beyond descriptive bibliometrics by conducting polynomial regression modelling and Chi-square tests. Specifically, polynomial regression and Chi-square tests were used to examine the non-linear growth trajectory of TPACK publications over time (Long & Ryoo, 2010). This enabled the study to capture acceleration, saturation, and fluctuation patterns in research output, which are often curvilinear and not adequately represented by linear models in scientometric studies. This approach has been applied in prior bibliometric research for examining complex temporal dynamics and forecasting trends with greater sensitivity to inflection points (e.g., Nyulas et al., 2025). Finally, Microsoft Excel was utilized for data cleaning, organization, and supplementary trend visualization to enhance transparency and reproducibility. The integration of these tools enabled methodological triangulation to strengthen analytical depth and validity.

Data Collection and Processing

Publications were retrieved from the WoS core collection, a comprehensive and multidisciplinary citation database recognized for high-quality and influential research. Journal articles were included to ensure data rigor, excluding book reviews, editorials, and conference papers. We searched the WoS "topic" field using the query: TS = ("technological pedagogical content knowledge" OR TPACK OR "techno-pedagogical content knowledge" OR "technology pedagogical content knowledge" OR "technological pedagogical-content knowledge") AND TS = ("science education" OR "science teaching" OR "science teacher*" OR biology OR chemistry OR physics OR "natural sciences"). This query captured all publications mentioning TPACK in science education in the title, abstract, or keywords. We limited the search to English-language publications published between 2014 and 2024 to reflect the sustained growth in TPACK research. All retrieved records were exported to EndNote for reference management, duplicate removal, and manual screening to remove irrelevant papers, ensuring a dataset focused on TPACK in science education. **Table 1** summarizes the publications included in the study.

Scientometric Techniques

Science mapping was conducted in the first stage using scientometric methods to quantitatively analyze annual publication counts and citation metrics. This was done to trace growth patterns and identify influential works, modelling publication growth trajectories through polynomial regression in SPSS and visualizing patterns in Excel. Country, institution, journal, and author-level contributions were further analyzed to determine leading contributors, prominent publication outlets, and geographic and institutional patterns of research productivity. This stage provided a comprehensive overview of the structural and intellectual landscape of TPACK research in science education. In the second stage, conceptual structure analysis was conducted using the Bibliometrix R package to examine the knowledge structure and thematic development of the field. Co-word analysis, keyword co-occurrence, thematic mapping, thematic evolution, and trend topic analyses were performed to identify the major research themes, conceptual relationships, and emerging directions in TPACK research. Together, these analyses complemented the science mapping results by providing insights into the conceptual organization and evolution of the research domain.

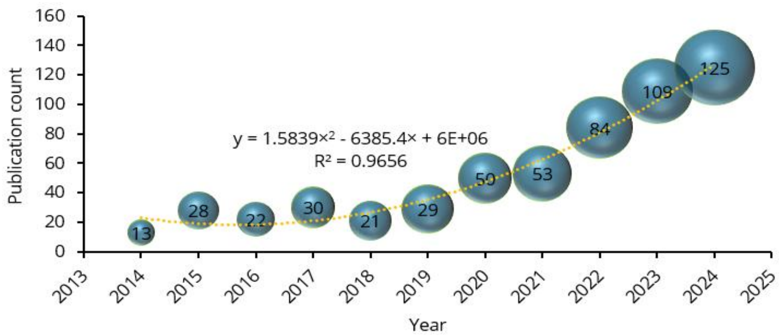

Figure 2. Temporal publication trends (the author's own analysis of the study dataset)

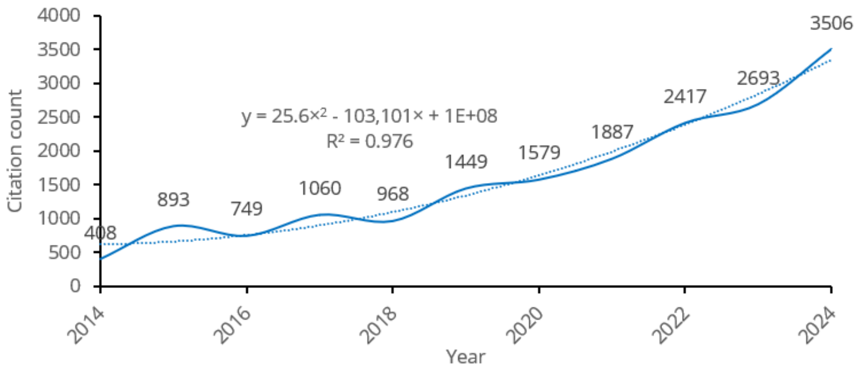

Figure 3. Temporal citation trends (the author's own analysis of the study dataset)

Table 2. Growth of publications

Year	Publication count	Percentage (%)
2014	13	2.30
2015	28	4.96
2016	22	3.90
2017	30	5.32
2018	21	3.72
2019	29	5.14
2020	50	8.87
2021	53	9.40
2022	84	14.89
2023	109	19.33
2024	125	22.16
Total	564	100

Data Analysis and Interpretations

Table 1 summarizes key data extracted from the WOS database between 2014 and 2024.

Publication and citation trends analysis

Polynomial regression analysis ($R^2 = 0.9656$ for publication count and $R^2 = 0.9760$ for citation count) revealed an accelerating trajectory of publications (**Figure 2**) and citations (**Figure 3**) over time. The positive quadratic coefficient (1.5839) confirms that growth is quadratic rather than linear, suggesting that research output will continue to increase rather than plateau. Notably, citation counts sharply rise from 2018 onward, indicating the field's growing recognition.

Growth of publications

The annual number of publications ranged from a low of 13 in 2014 to a peak of 125 in 2024, with an overall average of 51.27 per year. **Table 2** shows that the data reveal a consistent upward trajectory in the literature across the study period.

Table 3. Publications annual growth rate 2014-2024

Year	Publication count	AGR
2014	13	-
2015	28	115.38
2016	22	21.43
2017	30	36.36
2018	21	30.00
2019	29	38.10
2020	50	72.41
2021	53	6.00
2022	84	58.49
2023	109	29.76
2024	125	14.68

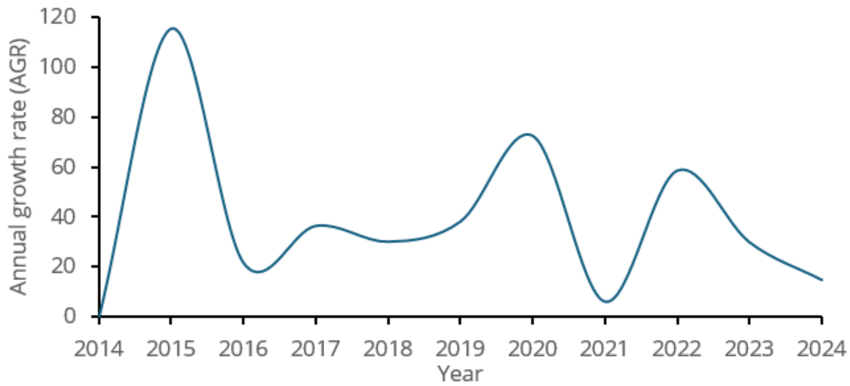

Figure 4. Annual growth rate (the author's own analysis of the study dataset)

Annual growth rate of publications

We computed the annual growth rate (AGR) using the following formula: $AGR = \frac{N_t - N_{t-1}}{N_{t-1}} \times 100$, where N_t is the number of publications in year *t* and N_{t-1} is the number in the preceding year.

Table 3 and **Figure 4** present the year-wise AGR of publications. The data indicate considerable fluctuations throughout the study period. The AGR increased steadily from 115.38 in 2014 to 30.00 in 2018, followed by a sharp rise from 38.10 in 2019 to 72.41 in 2020. Thereafter, the trend remained inconsistent, with noticeable year-to-year variations. These fluctuations reflect the absence of sustained annual growth in publication output. The apparent decline in AGR in 2024 should be interpreted with caution, as it may reflect delays in the publication process, with a portion of 2024 outputs likely appearing in 2025 or later.

Compound annual growth rate of the publications

The compound annual growth rate (CAGR) is derived by taking the nth root of the overall growth rate, where *n* represents the number of years in the study period. It can be expressed mathematically as follows: $CAGR = \left(\frac{N_{end}}{N_{start}}\right)^{\left(\frac{1}{\#\ of\ years}\right)} - 1$, where N_{start} = initial number of publications, N_{end} = final number of publications, and *n* = number of years.

Table 4 and **Figure 5** show that both the CAGR and year-on-year (YoY) growth (%) of publications declined from 215.38 in 2015 to 45.79 and 28.47 in 2024, respectively. Although annual output continued to rise, the downward trajectory of the CAGR indicates a gradual deceleration in the overall pace of growth, potentially reflecting the field's transition from rapid emergence to a phase of relative stabilization and maturity.

Table 4. CAGR of publications 2014-2024

Year	Publication count	Cumulative total	CAGR (%)	YoY growth (%)
2014	13	13	-	-
2015	28	41	215.38	215.38
2016	22	63	120.14	53.66
2017	30	93	92.68	47.62
2018	21	114	72.08	22.58
2019	29	143	61.54	25.44
2020	50	193	56.77	34.97
2021	53	246	52.20	27.46
2022	84	330	49.82	34.15
2023	109	439	47.85	33.03
2024	125	564	45.79	28.47

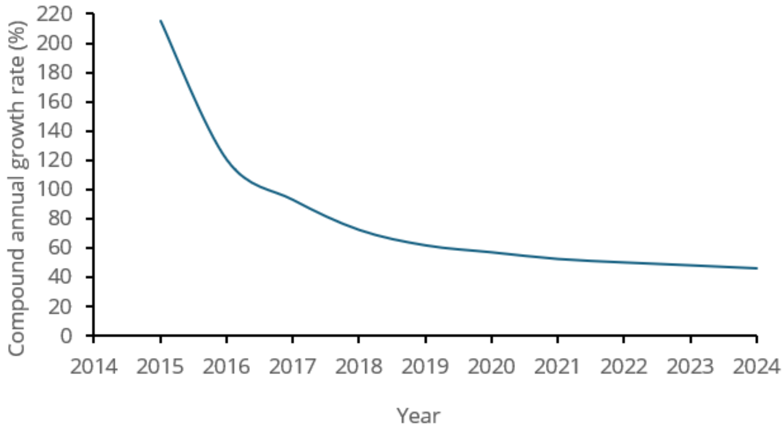

Figure 5. CAGR of publications (%) (the author's own analysis of the study dataset)

Relative growth rate

The relative growth rate (RGR) represents an increase in the number of articles or pages per unit of time. The mean RGR over a given interval can be computed using the following equation: *RGR:* $1 - 2^R = \frac{log_e W_2 - log_e W_1}{T_2 - T_1}$. Here, $1\text{-}2^R$ denotes the mean RGR over a given interval; $\log_e W_1$ and $\log_e W_2$ represent the natural logarithms of the initial and final number of articles, respectively. *T2-T1* represents the time interval, with *year* taken as the unit of time. Accordingly, $1\text{-}2^R$ (articles^{-1} year^{-1}) reflects the mean RGR per unit of articles per year.

As shown in **Table 5** and **Figure 6**, the RGR declined steadily from 1.15 in 2015 to 0.23 in 2018, followed by a slight increase to 0.30 in 2019 before decreasing again to 0.24 in 2021. These results indicate that the growth of the literature does not follow an exponential trajectory but rather an arithmetic one. This suggests that no explosive expansion in TPACK in science education literature occurred during the study period.

Table 5. RGR and DT of publications

Year	Publication count	Cumulative total	$\log_e W_1$	$\log_e W_2$	RGR	DT
2014	13	13	-	2.56495	-	-
2015	28	41	2.56495	3.71357	1.14862	0.60333
2016	22	63	3.71357	4.14313	0.42956	1.61327
2017	30	93	4.14313	4.53260	0.38946	1.77937
2018	21	114	4.53260	4.73620	0.20360	3.40375
2019	29	143	4.73620	4.96284	0.22665	3.05763
2020	50	193	4.96284	5.26269	0.29985	2.31119
2021	53	246	5.26269	5.50533	0.24264	2.85607
2022	84	330	5.50533	5.79909	0.29376	2.35906
2023	109	439	5.79909	6.08450	0.28541	2.42811
2024	125	564	6.08450	6.33505	0.25055	2.76586

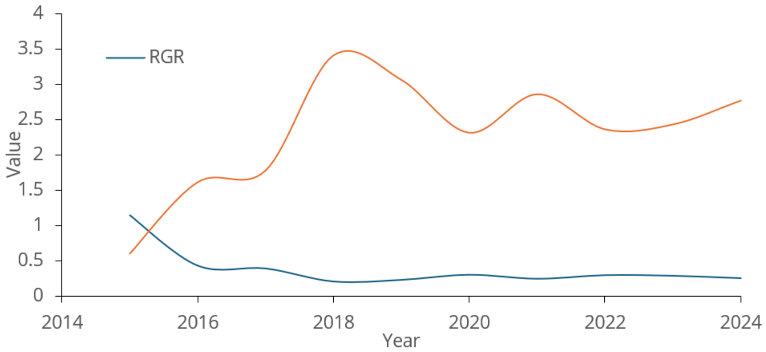

Figure 6. RGR and DT trends (the author's own analysis of the study dataset)

Doubling time

A direct relationship exists between the RGR and doubling time (DT). When the number of articles doubles within a given interval, the logarithmic difference between the initial and final counts equals the logarithm of 2. Using the natural logarithm, this value is 0.693, which leads to the formula for calculating the DT as follows: $DT = \frac{0.693}{R}$. Here, a shorter DT indicates more rapid expansion of the literature, whereas a longer DT reflects a slowdown in growth.

Accordingly, the DT for articles can be expressed as DT (a) = 0.693/(1-2*R*) (articles^{-1} year^{-1}). The year-wise analysis shows a steady increase in DT, rising from 0.60 years in 2015 to 3.40 years in 2018. A slight decline was observed in 2019 (3.06 years), followed by a further decrease to 2.77 years in 2024 (**Figure 6**). Although DT exhibits an upward trend, this pattern does not indicate accelerating growth, aligning with the CAGR analysis, which reflects a deceleration in research expansion. The findings suggest a shift from rapid growth (2014-2016) toward a more moderate and fluctuating expansion (2017-2024). The short DT in 2014 reflects an early surge in publications, while the subsequent increase to 2-3 years suggests the field is stabilizing and may be entering a phase of consolidation rather than explosive growth.

Trend analysis by the least squares method

We used the trend method to identify the long-term tendency in the time series data. This method involved fitting a straight line, also referred to as the *line of best fit*, to the observed data points. The line of best fit is defined such that the algebraic sum of the deviations of the observed values from the trend line equals zero, and that the sum of the squared deviations of the observed values from the trend line is minimized compared to any other possible line. The following equation represents the straight-line trend: $Y = a + bX$, where *Y* is the estimated trend value, *X* is the time variable (measured as deviations from the mean period), *a* is the intercept, indicating the trend value at the mean time, and *b* is the slope, indicating the rate of change per unit of time. We determined the parameters *a* and *b* using the least squares method by solving the system of normal equations: $\sum Y = Na + b\sum X$ and $\sum XY = a\sum X + b\sum X^2$, where *N* denotes the number of years (or periods) for which data is available. The time variable *X* can be measured from any arbitrary point of origin. However, for computational convenience, we took the midpoint of the time series as the origin in line with the least squares method. This approach ensured that the negative values of *X* in the first half of the series balance the positive values in the second half, which symbolically yields: $\sum X = 0$.

Under this condition, the two normal equations used to determine the constants *a* and *b* are simplified to: $\sum Y = Na \Rightarrow a = \frac{\sum Y}{N} = Y$ and $\sum XY = b\sum X^2 \Longrightarrow b\frac{\sum xy}{\sum x^2}$.

These simplified equations show that the constant *a* corresponds to the mean of the observed *Y* values, while the constant *b* represents the rate of change in the series over time. Hence, $a = \sum\frac{\sum Y}{N} = \frac{564}{11} = 51.27$ and $b = \sum\frac{\sum XY}{X^2} = \frac{4529}{506} = 8.95$. Therefore, substituting *a* and *b* values into the straight-line trend equation, the estimated trend line is obtained as: $Y = a = bX \Longrightarrow 51.27 + 8.95 \times X$.

To forecast the value for the year 2025, the time variable is taken as *X* = 12. $Y_{2025} = 51.27 + 8.95 \times 12 = 158.67$. Thus, the estimated publication count for 2025 is 159. This sustained increase in publication output

Table 6. Most productive countries/regions ranked by total number of publications

R	Country	2014-2024							2014-2018		2019-2024	
		TP	TP (%)	TC	C/P	SCP	MCP	MCP (%)	TP	TC	TP	TC
1	China	121	18.4	3,449	28.50	89	32	26.4	25	846	96	2,603
2	United States	92	14.0	7,766	84.41	85	7	7.6	25	1,227	67	6,539
3	Turkey	70	10.7	1,561	22.30	64	6	8.6	25	629	45	932
4	Taiwan	64	9.8	3,751	58.60	57	7	10.9	5	220	5	113
5	Indonesia	42	6.4	262	6.24	33	9	21.4	-	-	42	262
6	Spain	32	4.9	478	14.94	27	5	15.6	4	183	28	295
7	Germany	25	3.8	255	10.20	24	1	4.0	-	-	25	255
8	Australia	21	3.2	347	16.52	15	6	28.6	7	154	18	193
9	Singapore	21	3.2	2,153	102.52	10	11	52.4	8	614	13	1,539
10	South Africa	15	2.3	66	4.40	13	2	13.3	-	-	15	66
11	Malaysia	14	2.1	78	5.57	10	4	28.6	-	-	14	78
12	Brazil	12	1.8	36	3.00	10	2	16.7	-	-	12	36
13	Korea	10	1.5	79	7.90	7	3	30.0	-	-	10	79
14	India	9	1.4	38	4.22	6	3	33.3	-	-	9	38
15	Saudi Arabia	9	1.4	119	13.22	7	2	22.2	1	16	8	103
16	Finland	8	1.2	482	60.25	6	2	25.0	1	114	7	368
17	Iran	7	1.1	67	9.57	5	2	28.6	-	-	7	67
18	Netherlands	7	1.1	741	105.86	3	4	57.1	4	225	3	516
19	Thailand	7	1.1	80	11.43	6	1	14.3	-	-	7	80
20	Cyprus	6	0.9	672	112.00	6	0	0.0	1	4	5	668

Note. R: Rank; TP (%): Percentage of publications; C/P: Citations per publication; SCP: Single-country publications, 'domestic' papers with no international collaboration; MCP: Multiple-country publications, the number of publications produced through international cooperation; MCP (%): MCP percentage

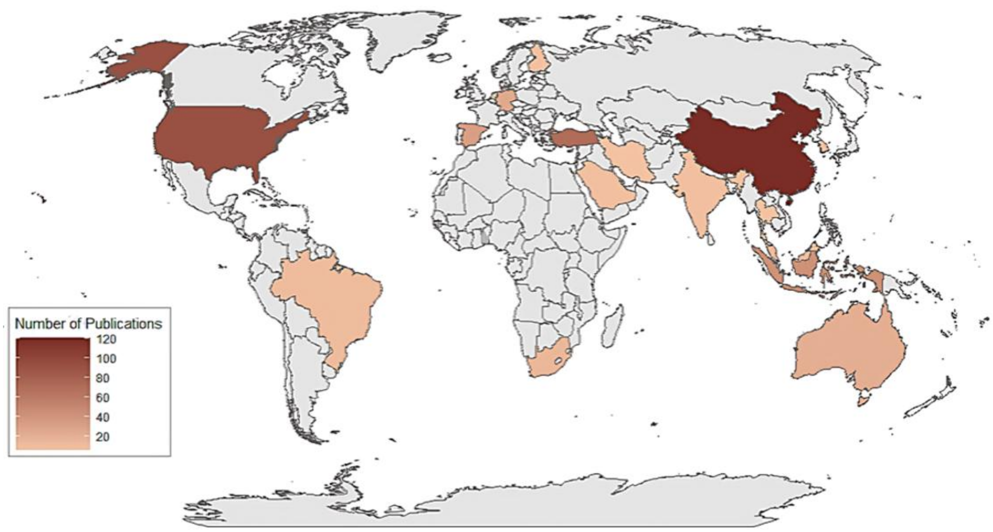

Figure 7. World map: Top productive countries (the author's own analysis of the dataset, visualized using R version 4.5.0 [Bibliometrix package])

confirms the expanding research activity in the field, which also poses challenges related to synthesizing the growing body of literature.

Most Productive Countries/Regions Based on Publications and Citations

Research contributions spanned 61 countries, with China, the United States, and Turkey emerging as the most prolific (**Table 6**).

Figure 7 shows regional output concentrations, with East Asia, North America, and parts of Europe dominating global scholarship.

The citation network (**Figure 8**) demonstrates the United States' dominance, with the largest node and densest linkages confirming its central influence in global scholarship. China, Taiwan, and some secondary actors (e.g., Turkey, Spain, and Australia) also exert notable influence. However, the overall structure reflects a highly unequal distribution of citation power concentrated in a few countries.

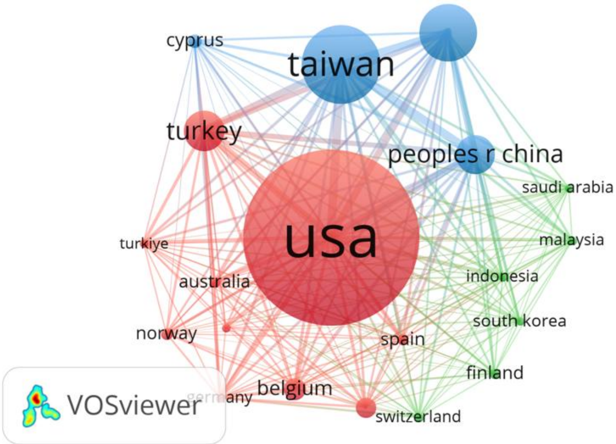

Figure 8. Countries' citation impact (the author's own analysis of the dataset, visualized using VOSviewer [version 1.6.20])

Table 7. Top institutions ranked by total number of publications and citations

R	Institution	Country	TP	TC	C/P	ARWU	QS
1	Nanyang Technological University	Singapore	34	2701	79.44	88	12
2	Chinese University of Hong Kong	Hong Kong	24	572	23.83	101-150	32
3	Beijing Normal University	China	18	423	23.50	101-150	247
4	National Taiwan Normal University	Taiwan	30	820	27.33	-	435
5	The Education University of Hong Kong	Hong Kong	15	144	9.60	801-900	530
6	National Taiwan University of Science and Technology	Taiwan	18	2137	118.72	901-1,000	345
7	The University of Hong Kong	Hong Kong	8	151	18.88	69	11
8	Central China Normal University	China	9	229	25.44	501-600	-
9	Monash University	Australia	6	51	8.50	76	36
10	Necmettin Erbakan University	Turkey	11	161	14.64	-	-
11	Universitas Negeri Malang	Indonesia	10	60	6.00	-	-
12	University of Seville	Spain	7	109	15.57	601-700	-
13	Arizona State University	United States	8	389	48.63	101-150	173
14	University of Amsterdam	Netherlands	6	290	48.33	101-150	53
15	Vrije Universiteit Brussel	Belgium	6	522	87.00	301	294
16	University of Georgia	United States	6	328	54.67	301-400	525
17	University of Twente	Netherlands	8	865	108.13	401-500	203
18	Gazi University	Turkey	10	124	12.40	901-1,000	1201
19	University of Alicante	Spain	8	162	20.25	15-19	781
20	Middle East Technical University	Turkey	7	440	62.86	-	-

Note. ARWU: The 2025 academic ranking of world universities (https://www.shanghairanking.com/rankings/arwu/2025); QS: World university rankings 2026 (https://www.qschina.cn/en/university-rankings/world-university-rankings/2026); & C/P: Citations per publication

Leading Institutional Contributors to the Field

Of the 595 institutions (top 20 in **Table 7**), Nanyang Technological, Beijing Normal, and the Chinese University of Hong Kong lead in productivity.

The productivity map (**Figure 9**) identifies Nanyang Technological University and National Taiwan Normal University as the leading contributors, with Hong Kong and Taiwanese institutions forming a dense, high-output cluster.

Leading journals on publications and citation impact

We analyzed 213 journals and ranked the top 20 based on their publication output and citation impact (**Table 8**). Among the leading journals, *Education and Information Technologies* is the most prolific (total publications [TP] = 51) but yields modest citation depth (total citations [TC] = 735; h-index = 16; g-index = 24; m-index = 2.00), with limited highly cited papers. In contrast, *Computers & Education* demonstrates clear dominance, achieving the highest impact (TC = 3,447; h-index = 26; g-index = 34; m-index = 1.53) and an intense concentration of influential works (h ≥ 300 = 4; h ≥ 100 = 13; h ≥ 50 = 9), supported by its leading impact factors (IF = 10.5; 5-year IF = 9.3). The *Australasian Journal of Educational Technology* and the *Journal of*

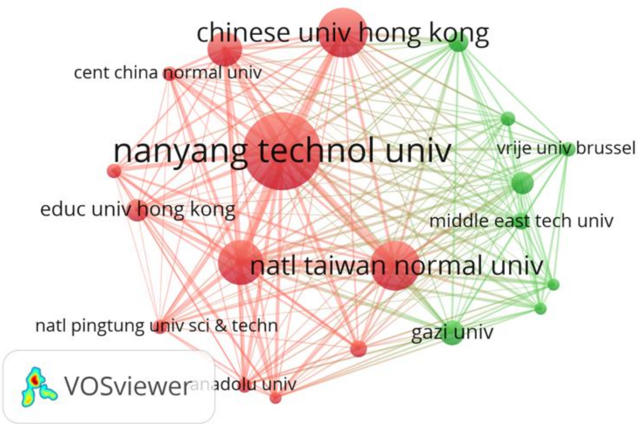

Figure 9. Institution productivity visualization (the author's own analysis of the dataset, visualized using VOSviewer [version 1.6.20])

Table 8. Bradford's law distribution of journals

Zone	Number of journals	Percentage of journals (%)	Description
Zone 1	10	4.69	Core journals (highest productivity)
Zone 2	27	12.68	Moderately productive journals
Zone 3	176	82.63	Low productivity/scattered journals
Total	213	100	

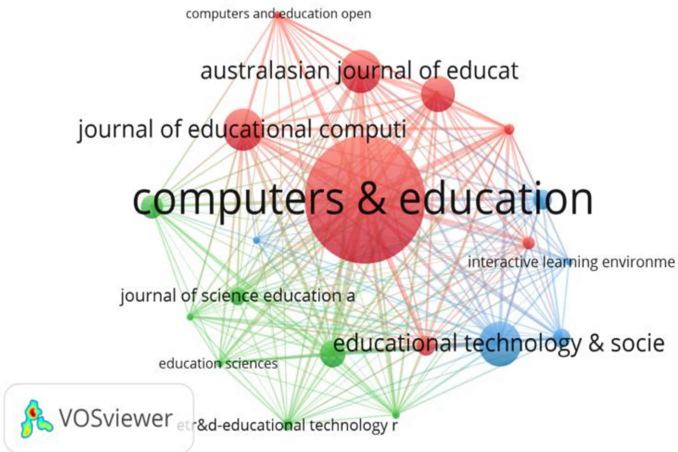

Figure 10. Journal citation network visualization (the author's own analysis of the dataset, visualized using VOSviewer [version 1.6.20])

Educational Computing Research occupy the mid-tier, each showing balanced performance (h-indices of 19 and 18) with influence concentrated at the h ≥ 50 level and competitive impact factors. The *Journal of Research on Technology in Education* has comparatively lower citation strength (TC = 292; h-index = 11) but is reinforced by favorable journal metrics (IF = 5.0; 5-year IF = 5.9), indicating emerging potential.

The citation network (**Figure 10**) reveals *Computers & Education* as the dominant and most interconnected hub, confirming its role as the field's flagship journal. Surrounding it, the *Australasian Journal of Educational Technology* and the *Journal of Educational Computing Research* form a dense core community, while *Educational Technology & Society* and the *Journal of Science Education and Technology* anchor distinct but linked clusters.

Testing Bradford's Law

Bradford's law of scattering posits that a few journals publish the most important articles, while the rest of the literature is scattered across a growing number of journals. If journals are divided into zones, each producing roughly the same number of relevant articles, then its mathematical form can be expressed as: $1 : n : n^2$, which is the approximate ratio of the number of journals in successive zones.

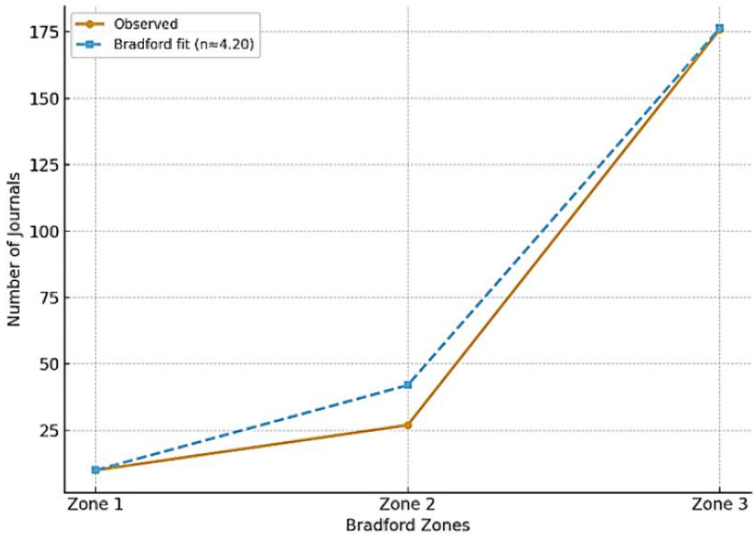

Figure 11. Bradford's law of scattering (10/27/176 zoning) (the author's own analysis of the dataset, visualized using R version 4.5.0 [Bibliometrix package])

- Zone 1: 'core journals' with the highest concentration of articles,
- Zone 2 and zone 3: progressively larger sets of journals producing fewer relevant articles each.

Journals were ranked in descending order of productivity and divided into three zones, each representing a comparable share of total articles (**Table 8**). The analysis identified the following final zoning:

- Zone 1: 10 journals
- Zone 2: 27 journals
- Zone 3: 176 journals

and Bradford's multipliers: $n_{21} = \frac{Zone\ 2}{Zone\ 1} = \frac{27}{10} =$ 2.70 and $n_{31} = \frac{Zone\ 3}{Zone\ 1} = \frac{176}{10} =$ 17.60. If Bradford's law held exactly, we would expect: $n_{31} \approx n_{21}^2$ = 7.29. But 2.70^2 = 7.29 is far below the observed 17.60. With alternate estimates of *n* computed as follows: $n \approx \sqrt{n_{31}}$ from zone 3 $\Longrightarrow n = \sqrt{17.6} \approx 4.20$.

We calculated the goodness of fit:

- Using *n* = 2.70 (from zone2/zone1), predicted zone3 journals = 10 × 2.70 = 72.9 vs. observed 176 → underestimates zone 3 by 103.1 journals (≈ 141% fewer than observed).
- Using *n* = 4.20 (from zone3), predicted zone2 journals = 10 × 4.20 = 42.0 vs. observed 27 → overestimates zone 2 by 15 journals (≈56% more than observed).

The resulting distribution corresponds to a mathematical ratio of 1:2.7:17.6. While the increase from zone 1 to zone 2 is broadly consistent with Bradford's expected pattern, the substantially larger number of journals in zone 3 indicates a high level of dispersion.

Figure 11 shows the observed data (solid line) contrasted with the theoretical Bradford fit (dashed line, *n* ≈ 4.20). The zone 2-derived multiplier (n ≈ 2.70) underpredicts the number of peripheral journals, while the zone 3-derived multiplier (n ≈ 4.20) overpredicts the intermediate zone. This divergence is standard in real bibliometric datasets and can result from heterogeneity in the topic, such as many single-article or low-output peripheral journals.

The Most Prolific Authors Based on Publications and Citation Impact

In keeping with the established tradition of recognizing leading scholars in bibliometric research, we analyzed 1,516 TPACK in science education authors based on productivity, citation count and h-index (**Table 9**). Chai Ching Sing of The Chinese University of Hong Kong emerged as the leading scholar. While established figures dominate the field, the rise of emerging voices such as author from South Africa highlights a global shift toward more geographically diverse contributions. This reflects the expanding international scope of TPACK in science education research.

Table 9. Goodness-of-fit test of Lotka's law (author productivity) and corresponding Chi-square contributions

n	Observed A (n)	Expected E (n) = 1,516 × 0.654/n^2	$\frac{(A(n) - E(n))^2}{E(n)}$
1	1,324	1,516 × 0.654/1^2 = 991.464	111.532
2	123	1,516 × 0.654/2^2 = 247.108	62.332
3	37	1,516 × 0.654/3^2 = 110.668	49.038
4	14	1,516 × 0.654/4^2=62.156	37.309
5	10	1,516 × 0.654/5^2 = 39.416	21.953
7	1	1,516 × 0.654/7^2 = 19.708	17.759
8	1	1,516 × 0.654/8^2 = 15.160	13.226
9	2	1,516 × 0.654/9^2 = 12.128	8.458
10	1	1,516 × 0.654/10^2 = 10.612	8.706
15+	3	Combined tai 1 = 1,516 × 0.654 & $\sum_{n\in\{152333\}} {}^{1}/_{n^2}$ ≈ 7,580	2.767

Note. Total χ^2 = 332.08 (df = 9, p < 0.001) & Critical χ^2 = 16.92 (α = 0.05)

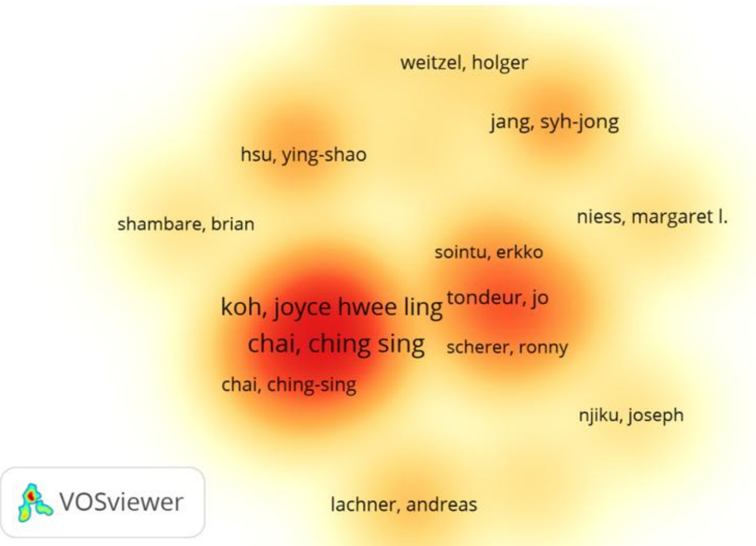

Figure 12. Network visualization of authors with ≥ 4 publications (the author's own analysis of the dataset, visualized using VOSviewer [version 1.6.20])

The VOSviewer density map (**Figure 12**) highlights Ching Sing Chai and Joyce Hwee Ling Koh as dominant contributors, supported by established figures like Jo Tondeur and Ronny Scherer. Emerging scholars such as author (South Africa), Ying-Shao Hsu, and Andreas Lachner appear at the periphery, signaling growing diversification and new research voices in the field.

Chi-square goodness-of-fit test for Lotka's law

Lotka's law posits that the number of authors making *n* contributions is proportional to $1/n^c$, where c is typically close to 2 (Lotka, 1926). To test this distribution, we fitted the observed frequency data of 1,516 authors' contributions (**Table 10** and **Table 11**) against the theoretical Lotka model: $P\ (n) = \frac{1}{n^c}\ /\ \sum_{k=1}^{N} \frac{1}{k^c}$, where *P (n)* is the theoretical proportion of authors with *n* publications, *c* is the Lotka exponent, and *N* is the maximum number of contributions observed.

The distribution of author productivity was analyzed using Lotka's Law, assuming the classical exponent *c* = 2. The observed frequencies were compared with the expected inverse square distribution. A Chi-square goodness-of-fit test was performed to assess conformity. The results yielded χ^2 = 332.08 (df = 9, p < 0.001), exceeding the critical value of 16.92 at the 0.05 significance level. The null hypothesis of conformity to Lotka's Law was therefore rejected. While the distribution exhibits a decreasing trend consistent with Lotka-type behavior, the statistical evidence indicates significant deviation from the theoretical model. This suggests a more uneven distribution of author productivity, characterized by a higher proportion of single-publication authors and a lower proportion of highly productive authors than expected.

Table 10. Top twenty journals with the most publications and citations

R	Source	TP	TC	C/P	h-index	g-index	m-index	h ≥ 300	h ≥ 100	h ≥ 50	IF (Q) 2024	5-year IF
1	Education and Information Technologies	51	735	14.4	16	24	2.00	0	0	5	5.4 (1)	5.7
2	Computers & Education	34	3,447	101.4	26	34	1.53	4	13	9	10.5 (1)	9.3
3	Australasian Journal of Educational Technology	30	1,168	38.9	19	30	1.27	0	5	12	3.3 (1)	4.6
4	Journal of Educational Computing Research	21	1,156	55.0	18	21	1.06	1	6	6	4.9 (1)	6.0
5	Journal of Research on Technology in Education	20	292	14.6	11	17	1.22	0	0	1	5.0 (1)	5.9
6	Technology Pedagogy and Education	16	339	21.2	10	16	0.77	0	1	1	2.5 (1)	3.7
7	British Journal of Educational Technology	15	532	35.5	11	15	0.55	0	3	3	8.1 (1)	8.1
8	Asia-Pacific Education Researcher	14	532	38.0	10	14	0.67	0	0	0	4.6 (1)	4.6
9	Education Sciences	14	125	8.9	6	11	1.50	0	0	0	2.6 (2)	2.7
10	Educational Technology & Society	13	1,223	94.1	10	13	0.63	3	3	0	6.0 (1)	5.7
11	Journal of Science Education and Technology	13	502	38.6	10	13	0.63	0	2	3	5.5 (1)	5,1
12	Computers and Education Open	13	41	3.2	4	5	1.00	0	0	0	5.7 (1)	6.1
13	Sustainability	12	230	19.2	7	12	1.00	0	0	2	4.6 (1)	4.7
14	Frontiers in Education	11	60	5.5	5	7	1.25	0	0	0	1.9 (2)	2.4
15	Educational Technology Research and Development	10	322	32.2	8	10	0.67	0	2	2	4.2 (1)	5.3
16	International Journal of Instruction	10	82	8.2	7	9	1.17	0	0	0	1.2 (-)	1.6
17	Journal of Computer Assisted Learning	9	979	108.8	7	9	0.44	1	3	2	6.0 (1)	5.7
18	Eğitim ve Bilim-Education and Science	8	70	8.8	6	8	0.46	0	0	0	0.6 (3)	0.9
19	Interactive Learning Environments	8	172	21.5	6	8	0.60	0	2	0	5.3 (1)	6.2
20	Contemporary Educational Technology	7	58	8.3	5	7	1.00	0	0	0	4.3 (1)	-

Note. R: Rank; C/P: Citations per publication; h-index; h ≥ 50, h ≥ 100, and h ≥ 300 indicate authors with at least 50, 100, and 300 publications cited at least the same number of times, respectively; h-index: A journal has an h-index of h if they have h publications each cited at least h times; g-index: A journal has a g-index of g if their top g publications together have at least g² citations; m-index: Normalizes the h-index by career length; IF (Q) 2025 = 2025 impact factor, with quartile ranking (Q1-Q4) in the subject category; 5-year IF: 5-year impact factor, averaging citations over the previous five years

Table 11. Distribution of articles across authors

n (papers)	Observed A (n)	Observed proportion P_{obs} (n)
1	1,324	0.873
2	123	0.081
3	37	0.024
4	14	0.009
5	10	0.007
7	1	0.001
8	1	0.001
9	2	0.001
10	1	0.001
15	1	0.001
23	1	0.001
33	1	0.001

To estimate the best-fitting parameter, we regressed the logarithm of the observed author frequencies (ln [*y*]) against the logarithm of their publication counts (ln [*n*]): $\ln(y) = a - c\ln(n)$. The fitted model gave:

- Intercept *(a)* = 5.85
- Slope (-*c*) = -2.16 (*SE* = 0.32, *t* = -6.76, *p* < 0.001)
- $R^2 = 0.82$

Thus, the estimated Lotka exponent is: $c \approx 2.16$. The regression analysis produced an estimated Lotka exponent of c ≈ 2.16, slightly steeper than the classical value of 2, with a strong descriptive fit ($R^2 = 0.82$). This indicates that author productivity exhibits an inverse power-law relationship characteristic of Lotka-type behavior. But Chi-square goodness-of-fit test ($\chi^2 = 332.08$, df = 9, p < 0.001) rejected the null hypothesis of conformity to Lotka's Law, indicating that the observed distribution differs significantly from the theoretical

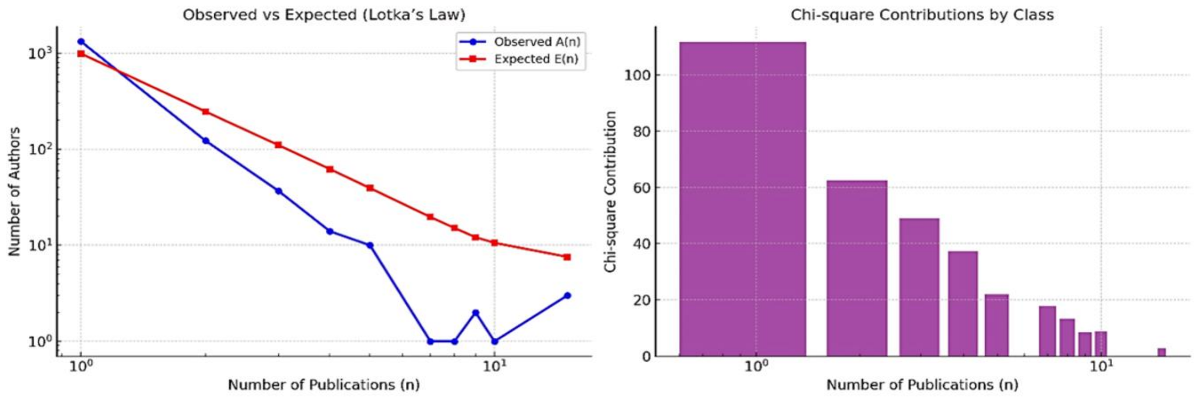

Figure 13. Comparison of observed and expected author productivity under Lotka's law (the author's own analysis of the dataset)

Table 12. The top twenty most prolific TPACK authors in science education

R	Author(s)	Profile/author page (direct link)	h-index	g-index	m-index	TP	TC	PYS
1	Chai Ching Sing	https://www.fed.cuhk.edu.hk/cri/faculty/prof-chai-ching-sing/	26	33	1.63	33	2,584	2010
2	Koh Joyce Hwee L	https://profiles.waikato.ac.nz/joycehweeling.koh	20	23	1.25	23	2,040	2010
3	Tsai Chin-Chung	https://scholar.lib.ntnu.edu.tw/en/persons/chin-chung-tsai	13	15	0.81	15	1,741	2010
4	Liang Jyh-Chong	https://scholar.lib.ntnu.edu.tw/en/persons/jyh-chong-liang	8	10	0.62	10	233	2013
5	Jang Syh-Jong	https://www.researchgate.net/profile/Syh-Jong-Jang	9	9	0.56	9	549	2010
6	Tondeur Jo	https://researchportal.vub.be/en/persons/jo-tondeur	9	9	0.69	9	648	2013
7	Baran Evrim	https://faculty.sites.iastate.edu/ebaran	8	8	0.53	8	501	2011
8	Voogt Joke	https://orcid.org/0000-0001-5035-9263	7	7	0.50	7	397	2012
9	Hsu Chung-Yuan	https://scholar.google.com/citations?hl=en&user=JNDlvsUAAAAJ	5	5	0.39	5	151	2013
10	Hsu Ying-Shao	https://scholar.lib.ntnu.edu.tw/en/persons/ying-shao-hsu	5	5	0.42	5	271	2014
11	Jong M Siu-Yung	https://www.fed.cuhk.edu.hk/cri/faculty/prof-jong-siu-yung-morris/	5	5	0.71	5	118	2019
12	Niess Margaret L.	https://engineering.oregonstate.edu/people/maggie-niess	5	5	0.33	5	205	2011
13	Yeh Yi-Fen	https://scholar.lib.ntnu.edu.tw/en/persons/yi-fen-yeh	5	5	0.42	5	271	2014
14	Bilici S Canbazoglu	https://dergipark.org.tr/en/pub/%40sedefbilici	4	5	0.31	5	172	2013
15	Lachner Andreas	https://scholar.google.com/citations?user=zE3pSR0AAAAJ&hl=en&oi=ao	4	5	0.80	5	99	2021
16	Tokmak H Sancar	https://apbs.mersin.edu.tr/profiles_mail/hsancartokmak	4	5	0.31	5	57	2013
17	Weitzel Holger	https://loop.frontiersin.org/people/2131338/overview	3	5	0.75	5	47	2022
18	Chen Yang-Hsueh	https://nutn.academia.edu/YangHsuehChen	4	4	0.33	4	90	2014
19	Petko Dominik	https://scholar.google.com/citations?user=grDH6AwAAAAJ&hl=en&oi=ao	3	4	0.50	4	278	2020
20	Shambare Brian	https://scholar.google.com/citations?hl=en&user=ZEPLg8EAAAAJ	2	2	1.00	4	47	2024

Note. R: Rank & PYS: Publication year start (the year a given document was published)

expectation. This deviation from classical Lotka distribution likely reflects the emerging and dispersed nature of the research, where many scholars contribute only once or twice without sustaining long-term publications.

The left panel in **Figure 13** plots the observed distribution of authors by number of publications (blue line) against the expected values derived from Lotka's theoretical formulation (red line) on a log-log scale. The right panel displays the Chi-square contributions for each productivity class, showing that the largest deviations stem from single- and two-publication authors (**Table 12**).

Most Influential Publications Based on Citation Metrics

We examined TPACK publications meeting a threshold of at least 100 citations per article to capture the field's most influential contributions. The citation network (**Figure 14**) and top-cited authors (**Table 13**) underscore the foundational impact of *Mishra and Koehler's (2006)* seminal paper, which remains the intellectual cornerstone of TPACK scholarship. Surrounding documents, including *Voogt et al. (2013)*, *Koh et al. (2014)*, *Archambault and Barnett (2010)*, and *Niess (2011)*, function as secondary hubs, advancing the framework into teacher education and applied contexts. More recent works, such as *Tondeur et al. (2020)*, *Schmid et al. (2021)*, and *Celik (2023)*, signal a broadening of influence, while newer studies like *Dong et al. (2020)* reflect emerging directions and rapid uptake in the field.

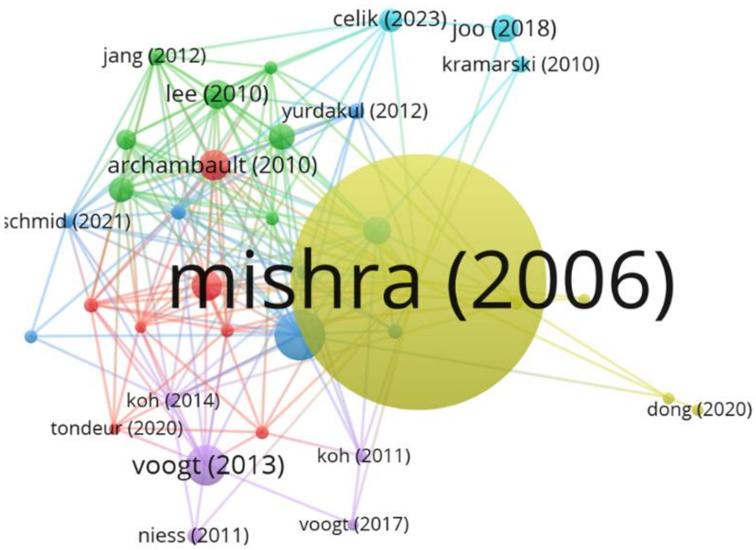

Figure 14. Citation network analysis (the author's own analysis of the Scopus dataset, visualized using VOSviewer [version 1.6.20])

Table 13. Top twenty most cited publications

R	Paper	DOI	TC	C/Y	NTC
1	Mishra and Koehler (2006)	https://doi.org/10.1111/j.1467-9620.2006.00684.x	4,540	227.00	1.97
2	Angeli and Valanides (2009)	https://doi.org/10.1016/j.compedu.2008.07.006	615	36.18	1.64
3	Voogt et al. (2013)	https://doi.org/10.1111/j.1365-2729.2012.00487.x	468	36.00	7.72
4	Graham (2011)	https://doi.org/10.1016/j.compedu.2011.04.010	327	21.80	2.66
5	Archambault and Barnett (2010)	https://doi.org/10.1016/j.compedu.2010.07.009	320	20.00	1.55
6	Lee and Tsai (2010)	https://doi.org/10.1007/s11251-008-9075-4	311	19.44	1.50
7	Chai et al. (2013)	https://doi.org/10.30191/ETS.201304_16(2).0004	297	22.85	4.90
8	Joo (2018)	https://doi.org/10.1080/1475939X.2019.1569554	283	35.38	5.54
9	Chai et al. (2010)	https://www.jstor.org/stable/10.2307/jeductechsoci.13.4.63	278	17.38	1.34
10	Chai et al. (2011)	https://doi.org/10.1016/j.compedu.2011.01.007	254	16.93	2.06
11	Celik (2023)	https://doi.org/10.1016/j.chb.2022.107468	243	81.00	27.74
12	Koh et al. (2010)	https://doi.org/10.1111/j.1365-2729.2010.00372.x	195	12.19	0.94
13	Jang and Tsai (2012)	https://doi.org/10.1016/j.compedu.2012.02.003	168	12.00	2.38
14	Yurdakul et al. (2012)	https://doi.org/10.1016/j.compedu.2011.10.012	151	10.79	2.14
15	Niess (2011)	https://doi.org/10.2190/EC.44.3.c	151	10.07	1.23
16	Kramarski and Michalsky (2010)	https://doi.org/10.1016/j.learninstruc.2009.05.003	144	9.00	0.70
17	Schmid et al. (2020)	https://doi.org/10.1016/j.compedu.2020.103967	140	23.33	5.94
18	Lin et al. (2013)	https://doi.org/10.1007/s10956-012-9396-6	133	10.23	2.19
19	Doering et al. (2009)	https://doi.org/10.2190/EC.41.3.d	133	7.82	0.36
20	Jang and Chen (2010)	https://doi.org/10.1007/s10956-010-9222-y	129	8.06	0.62

Note. C/Y: citations per year & NTC: Normalized TC

Core Topics and Emerging Research Themes

Keywords and thematic evolution analysis

Keywords encapsulate an article's central focus, and their frequency and co-occurrence illuminate dominant research themes (Radhakrishnan et al., 2017). **Figure 15** presents the twenty most frequent keywords. *Technological pedagogical content knowledge* remains the most prominent and consistently growing theme, accompanied by parallel increases in *technology integration, teacher education*, and *pre-service teachers*, underscoring its central role in teacher preparation. Since 2020, rising emphasis on *professional development, teacher training,* and *self-efficacy* reflects a shift toward *applied* and *psychological dimensions of digital pedagogy*, while the expansion into *mathematics education, science education, ICT,* and *higher education* demonstrates the broadening scope of application across disciplines and contexts.

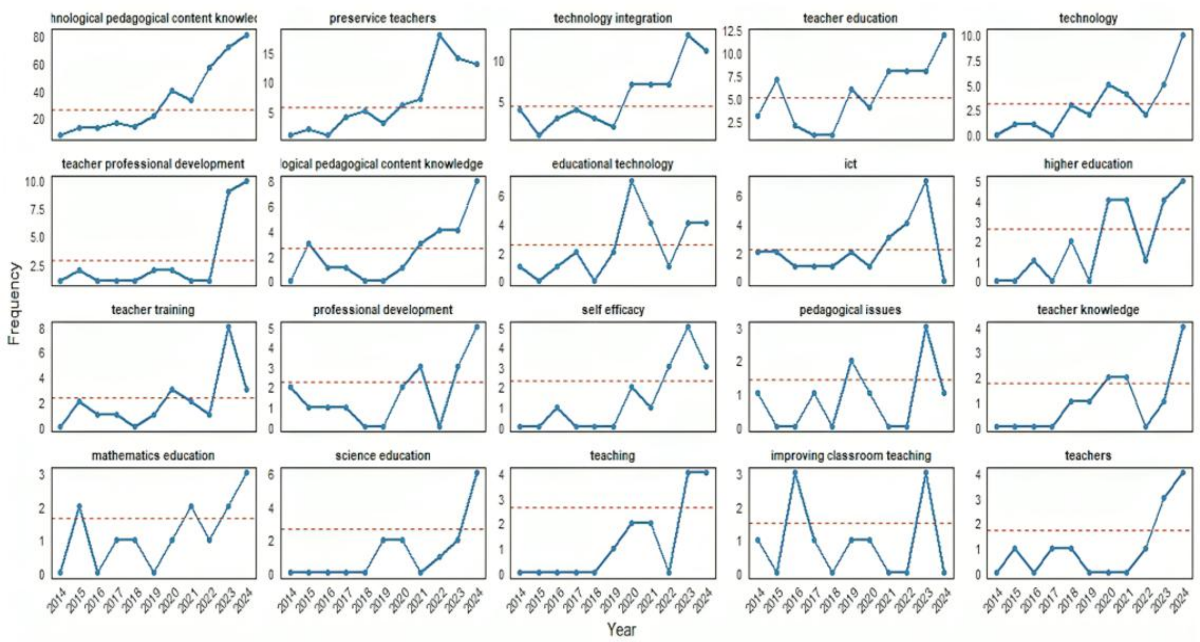

Figure 15. Top twenty keyword trends (the author's own analysis of the dataset, visualized using R version 4.5.0 [Bibliometrix package])

DISCUSSION

This scientometric review demonstrates that TPACK research in science education has advanced from its formative stage into a consolidated and globally recognized domain. The accelerating trajectory of publications and citations, confirmed through polynomial regression models, reflects the momentum the field has gained over the past decade. Earlier bibliometric reviews (e.g., Tondeur et al., 2020; Voogt et al., 2013) also documented accelerating growth, followed by signs of stabilization. The present analysis confirms this trajectory but makes a novel contribution by showing that this transition is not only statistical but also conceptual in science education. The early rapid expansion (2014-2016) gave way after 2017 to consistent productivity coupled with thematic diversification. This indicates that the field has entered a maturity phase where volume alone is no longer the defining marker of progress.

Geographical and institutional trends reinforce this developmental arc. The United States, China, and Turkey dominate output and citation influence, a pattern consistent with prior global reviews that highlighted the concentration of knowledge production in a few regions (Lee et al., 2022; Yalçın & Yayla, 2016). However, this study has gone further by documenting the significant rise of East Asian institutions, particularly Nanyang Technological University, Beijing Normal University, and the Chinese University of Hong Kong, as hubs of intellectual influence. Unlike earlier studies that emphasized Western dominance, the findings reveal a multipolar structure that reflects global realignments in educational research. Yet, the uneven distribution of contributions underscores persistent inequalities, extending prior critiques of geographic imbalance and raising new questions about inclusivity and knowledge transfer across diverse educational contexts.

The stratification of publishing outlets further illustrates the consolidation of the field. *Computers & Education* is the flagship journal, consistent with its role in setting general agendas in educational technology research. This observation is reported in various studies, including those by Karampelas (2023) and Yalçın and Yayla (2016). What this review adds is the nuanced recognition of a layered journal ecology. While journals such as *Education and Information Technologies* and the *Australasian Journal of Educational Technology* provide volume, their lower citation intensity reinforces a hierarchy of influence. Moreover, the deviations from the Bradford's law revealed in this study suggest a distinctive openness of TPACK in science education to interdisciplinary diffusion, extending beyond the boundaries captured in prior reviews. Similarly, the author productivity pattern aligns with Lotka's law but with a steeper decline, showing stronger dominance by a handful of scholars such as Ching Sing Chai and Joyce Hwee Ling Koh. Notably, dispersed authorship reveals a sharper asymmetry that signals both consolidation around key figures and fragmentation at the margins.

The intellectual architecture of the field remains firmly anchored in Mishra and Koehler's (2006) seminal framework, reaffirming findings from prior reviews. However, this study provides more insights into how later works, by Voogt et al. (2013) on teacher education, and by Tondeur et al. (2020), Schmid et al. (2021), and Celik (2023) on professional development and psychological constructs, have collectively shifted the field from validation of the framework toward its contextual and psychological enrichment. Thematic evolution analysis confirms this broadening from early emphases on 'technology integration' and 'teacher education' have expanded to themes of 'self-efficacy,' 'professional development,' and 'higher education.' While prior reviews acknowledged diversification, this study provides unique evidence that TPACK in science education has reached a stage where psychological and institutional dimensions are not peripheral but integral, representing a distinctive trajectory compared with general educational technology research.

CONCLUSION AND IMPLICATIONS

This scientometric review establishes that TPACK in science education has matured into an influential form of teacher knowledge, characterized by accelerating yet stabilizing growth that reflects both consolidation and diversification. The findings carry important implications for research. The partial deviations from Bradford's and Lotka's laws highlight how conventional bibliometric models inadequately represent interdisciplinary and practice-oriented domains. This indicates the need for more context-sensitive analyses of teacher knowledge research. The thematic broadening into teacher self-efficacy, professional development, and higher education demonstrates that TPACK has evolved into a multi-dimensional knowledge that captures the cognitive, affective, and practical dimensions of teaching with technology. Practically, these developments inform teacher education programs by guiding the design of targeted professional development and supporting more effective integration of technology in classroom practice. The findings of this study have clear practical implications for science education and teacher development. For teacher educators, they underscore the need to design professional development programs that build not only technological and pedagogical knowledge, but also teachers' self-efficacy, confidence, and reflective capacity in integrating digital tools meaningfully. For schools and policymakers, the results provide evidence to prioritize sustained, targeted investment in continuous training that bridges the gap between theory and classroom practice, particularly in under-resourced contexts where implementation challenges are more acute.

Although this study captures publication trends, the findings indicate that the field is still expanding and diversifying, particularly with the rapid integration of AI, adaptive learning systems, and other emerging educational technologies. Researchers, therefore, should continue to explore how these developments reshape the conceptual boundaries and practical applications of TPACK across different educational settings. In addition, more context-specific research is needed to understand how TPACK is enacted in under-resourced and diverse classroom environments, as well as how it influences teacher decision-making and instructional design in practice. Such work will strengthen the explanatory power of the framework and ensure its continued relevance in rapidly changing educational landscapes.

Limitations and Future Directions

Although the review provides comprehensive insights, several limitations should be acknowledged. This review is subject to several limitations. Restricting the analysis to WoS publications ensured rigor but excluded work from other databases and non-English outlets, potentially underrepresenting contributions from regions outside the dominant English-speaking sphere. Scientometric techniques also privilege structural patterns over interpretive depth, meaning the quality of pedagogical innovations or the richness of theoretical advancement cannot be fully captured. Despite these constraints, this study provides the first systematic evidence of how TPACK in science education has matured into a consolidated, multi-dimensional form of teacher knowledge. Future research should compare trajectories across domains, integrate scientometric and qualitative approaches, and track long-term developments to assess whether stabilization leads to deeper integration or new directions shaped by emerging technologies.

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