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Bibliometric analysis of pedagogical content knowledge: Countries, authors, and fields of knowledge

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Abstract

Pedagogical content knowledge (PCK) is a key construct that emerges as distinct from both pedagogical and disciplinary knowledge, essential for understanding how teacher training should be structured. Since its genesis, it has been the subject of thousands of studies, and although there are reviews within each disciplinary PCK area (e.g., PCK in mathematics), there are no bibliometric analyses that allow for the recognition of trends and gaps in productivity in the field of teaching in general. The aim of the present study was to identify such patterns through a review of high-impact specialized journals. For this purpose, 1,942 Web of Science articles were analyzed with various bibliometric parameters and digital visualization software. The results show a series of trends not described in previous literature. The implications for research on teacher training are discussed, considering the initial intent behind the construct's formulation and its relevance to contemporary educational challenges, and new lines of research are proposed.

Keywords: pedagogical content knowledge, PCK, bibliometric analyses, science education, mathematics education, TPACK

INTRODUCTION

Pedagogical content knowledge (PCK) is "the knowledge of, reasoning behind, and enactment of the teaching of particular topics in a particular way with particular students for particular reasons for enhanced student outcomes" (Carlson et al., 2015, p. 24). The term, originally coined by Shulman (1986, 1987), has become one of the constructs that supports most of the research on teaching profession and instruction (Ananin & Lovakov, 2022), and a robust framework for illustrating central characteristic of teachers' knowledge (Erduran & Guilfoyle, 2022), taking on different forms and models (van Driel et al., 2023), as a core element of teacher training programs (Hagevik et al., 2010) and definitions of teacher training standards in various countries around the world. Since there is evidence that a teacher's PCK is a significant factor for their students' learning (Kunter et al., 2013), understanding the PCK of specific content for teachers across all areas can help direct efforts towards more effective teaching.

Although Shulman (1986) defined the concept without considering any specific disciplinary area, since 1990s research on PCK gained significant momentum, researchers in mathematics and science teacher education were the ones who embraced the construct most enthusiastically and developed it progressively (Berry et al., 2015; Gess-Newsome & Lederman, 1999; Hume et al., 2019; Vergara et al., 2021; Wilson et al., 2019). This exploration aimed to identify the sources of this knowledge (Santibáñez et al., 2021), its components (Magnusson et al., 1999; Park & Chen, 2012), the way it develops (Schneider & Plasman, 2011), establish its relationship with disciplinary knowledge (Rollnick, 2017), identify its manifestations at different levels of

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Contribution to the literature

- This article contributes to the literature on PCK by providing a comprehensive bibliometric analysis of its exponential growth from 1988 to 2023 in the Web of Science (WoS) database.
- The study identifies prolific researchers clustered in the fields of mathematics and sciences, highlighting the significance of TPACK in contemporary educational discourse.
- It reveals the top contributing countries, including the United States, Germany, and China. Notably, the findings indicate a limited productivity in the humanities, despite the construct's broad applicability to teacher knowledge, thus opening avenues for future research in these areas.

education (Appleton, 2006; Lee et al., 2007; Li et al., 2021), and propose ways to evaluate it (Baxter & Lederman, 1999; Park & Suh, 2015). In this way, it was established that PCK was tacit knowledge (Henze & van Driel, 2015), topic-specific (Abell, 2008), had a declarative and procedural dimension (Schmelzing et al., 2013), could be developed throughout initial and continuous training (Zhang et al., 2015), was more influenced by reflective practice than by the teacher's age, and could promote reflection on one's own practice (Nilsson & Karlsson, 2019). Understanding its relationship with student learning has been more complex (e.g., Alonzo et al., 2012; Gess-Newsome et al., 2019; Mahler et al., 2017), although the disparate results of both variables may be due to the consideration of factors related to the school context and the conditions of the students themselves (Ergönenç et al., 2014).

Over more than three decades, research on PCK has given rise to numerous models, both descriptive-explanatory and predictive (Berry et al., 2016). These models are frequently used to guide various aspects of teacher training (Nilsson & Elm, 2017) and to understand the series of variables that allow a novice teacher to become an expert (Luft et al., 2022; Schneider & Plasman, 2011). The maturity of the construct has enabled it to be incorporated into public policy in several countries (e.g., Chantaranima & Yuenyong, 2017; CPEIP, 2021; Hagevik et al., 2010; Lavonen, 2018), promoted the development of teacher supervision and evaluation systems (Yang et al., 2018), and constituted the theoretical basis of TPCK, focused on the teacher knowledge required for technology use (Mishra & Koehler, 2006), a key aspect of contemporary teaching.

The link between PCK and subject-specific pedagogy, or the specific nature of each specialty, has led research on the PCK of each subject to follow separate paths (Cooper & van Driel, 2019). Since it is only possible to conduct research on PCK within the framework of a specific area of knowledge (Abell, 2008) and the findings of each study are necessarily limited by the PCK of the researcher (Park & Suh, 2015), it is complex for a single researcher to address questions, hypotheses, or models that encompass more than one area. In this sense, research productivity on PCK is asymmetrical between disciplines (Berry et al., 2016), and the synergy between researchers from different areas seems concentrated between science and mathematics (Chan & Hume, 2019) despite the common theoretical basis valid for all disciplinary areas. Thus, one of the aims of this bibliometric study is to illustrate how a critical mass of studies on this construct has emerged, enabling us to identify connections among authors and subtopics. Revealing these lines of convergence provides significant value for diverse stakeholders. For researchers, they highlight commonalities that can foster collaborative studies across disciplines. For teacher educators, particularly those working in multidisciplinary contexts like elementary education, these insights guide the development of integrated training programs. Policymakers can also benefit by reconsidering the reliance on PCK as the sole framework for teacher education standards, ensuring that they account for the disparities in research productivity across domains. Additionally, addressing these asymmetries promotes interdisciplinary dialogue and helps ensure that PCK frameworks are applied more effectively and equitably. Such reflections are crucial for creating teacher education policies that are both inclusive and evidence-based.

THEORETICAL FRAMEWORK

Teacher Training and PCK Development

The possibility of nurturing a new generation of citizens capable of addressing society's major issues is intrinsically linked to access quality education (Reimers, 2020). This, in turn, largely depends on the quality of teachers who are trained and retained within the school system (Escribano Hervis, 2018). At least three significant threats hinder these goals: the lack of interest in pursuing studies in pedagogy, insufficient improvement in the quality of teaching, and high rates of teacher attrition.

The lack of interest in studying pedagogy and becoming a teacher has been noted in numerous studies (Mombaers et al., 2023), and although it is a multifactorial challenge, it is closely associated with the social recognition of the teaching profession (Alvariñas-Villaverde et al., 2022). In general, the complexity of teaching is not well understood, and the type of professional knowledge a teacher requires is often invisible or difficult to recognize (Loughran, 2016). A profession that lacks recognition and is undervalued does not seem attractive to young people (Kraft & Lyon, 2024). Certainly, it is a difficult task to accomplish, and although progress has been made in certifying teacher training programs, it is also true that a 4- or 5-year curriculum seems insufficient for the range of knowledge that must be deployed. In this sense, it is crucial to have professional development programs that update and guide the task of teaching based on robust theoretical frameworks. Paradoxically, the criteria for effective professional development are stringent and often overlooked, even by universities offering such programs (Drăghicescu et al., 2018).

Considerable attention is given to disciplinary updates (e.g., climate change for science teachers) and pedagogical advancements (e.g., inclusive classrooms), but less emphasis is placed on the knowledge needed to effectively teach subjects defined within each country's curriculum frameworks (van Driel & Berry, 2012), which naturally impacts learning outcomes. Difficulties of this kind, combined with the workload, lack of professional projection and social recognition, have promoted a growing wave of teacher attrition (González-Escobar et al., 2020). All the aforementioned factors underscore the urgency of addressing teacher training, identifying their own learning progressions, establishing consensus models, and educating university trainers capable of guiding these processes.

PCK presents a potent response to this challenge for several reasons. Firstly, the research it has generated has elucidated many of the tasks, actions, and types of decisions that teachers make, which often remain implicit even to the professionals themselves (Henze & van Driel, 2015). Secondly, PCK is a concept applicable across all disciplines and educational levels. It integrates constructs from established traditions such as German and French didactics (Depaepe et al., 2013) and contextualized teaching (Ambrose et al., 2013). Thirdly, PCK facilitates the development of progress indicators across its various components. For instance, it allows for setting expectations for newly graduated teachers regarding their understanding of students' ideas about a topic, compared to expert teachers who blend their experience with research findings (Schneider & Plasman, 2011).

Study of PCK and Disciplinary Asymmetry

Research on PCK has focused on gathering evidence on how this knowledge manifests, is retrieved, and evaluated in both pre-service and in-service teachers (Park & Suh, 2015). The systematic review of this research, coupled with existing knowledge on teacher professional development, has led to the creation of numerous continuing education programs designed to enhance the PCK of participating teachers (Hill & Ball, 2004). These programs have been evaluated using quasi-experimental designs, revealing the complexity involved in fostering individual PCK development. Concurrently, they have identified general trends and specific PCK characteristics tailored to particular school subjects (e.g., natural selection: Becerra et al., 2023; geometry: Kurt-Birel et al., 2020).

In the case of science, the Magnusson model (Magnusson et al., 1999) is the most widely used in empirical research, describing the specific components of teachers' knowledge. Concurrently, progress has been made in consolidating a consensus model that describes the determining factors (Gess-Newsome, 2015), as well as the relationship between personal and collective PCK (Behling et al., 2022; Carlson et al., 2019). To this end, two international meetings of specialists have been held, specific books have been published, and it is a prevalent topic at science education conferences. Quantitative and qualitative methods have been defined to evaluate the PCK of specific topics, with specialists in elementary and secondary education teachers, as well as professional development programs to promote the PCK of in-service teachers.

A similar situation occurs with mathematics PCK, where the most influential model has been that of Hill et al. (2008). This model defines the 'content knowledge required to teach mathematics,' distinguishing proper PCK from conceptual knowledge of mathematics while incorporating several components of the Magnusson model (Magnusson et al., 1999). However, despite the proliferation of multiple approaches, specialists have not yet succeeded in consolidating a unified consensus model. Empirical research is abundant, developed through large-scale studies with pencil-and-paper questionnaires and more qualitative and comprehensive guidelines (Depaepe et al., 2013). Similar to science PCK, these studies have focused on both pre-service and in-service teachers.

In the context of history education, studies on PCK have predominantly been qualitative and involved limited participant numbers, lacking a specific model or systematic definition (Tuithof et al., 2019). Noteworthy among these is the model proposed by Monte-Sano and Budano (2013), where each component of PCK is explicitly linked to its corresponding teaching and learning processes. In areas such as physical education or language, the original Shulman (1986) model's logic has been preferred, maintaining a predominantly transformative view (Berry et al., 2016). As stated by Nilsson and Elm (2017), PCK serves as a heuristic concept for understanding the intricate knowledge teachers possess about teaching and how this knowledge evolves over extended periods. This condition holds true for any pedagogical context, at any educational level.

Bibliometric Studies

When addressing a construct that generates thousands of studies annually, one effective approach to synthesizing the overwhelming volume of research is through bibliometrics (Donthu et al., 2021; Shiffrin & Börner, 2004). While several of the articles cited above are systematic reviews of PCK, bibliometric analyses offer a complementary method. Unlike systematic reviews, which focus on a selected subset of studies, bibliometric analyses encompass a broader array of articles within a specific field, providing a comprehensive view of trends and methodologies. This capability to examine a vast body of scientific literature facilitates the identification of emerging patterns with greater objectivity (Mukherjee et al., 2022).

In this context, network visualizations serve as essential tools in bibliometric analyses (Güner & Gökçe, 2021). These networks, often referred to as nomological networks, depict the structural interconnections between variables or concepts within a field. By representing nodes as variables (such as authors or keywords) and links as relationships, these networks reveal complex patterns and relationships that enhance our understanding of the domain's structure and dynamics (Yig, 2022). Such visualizations are commonly used in bibliometric studies to illustrate the connections and thematic clusters within large bodies of research.

There is a notable absence of bibliometric-based reviews within the domain of PCK, whether within specific disciplines or considering the construct more broadly. Undertaking such a review would have significant implications, as it is essential to first ascertain advancements within each discipline to facilitate interdisciplinary dialogue among teacher educators. Despite existing systematic reviews on PCK in subjects such as science, mathematics, and history, there appears to be limited awareness regarding progress in other disciplines, with some fields being underrepresented. This gap seems counterproductive given the substantial annual output of PCK-related literature, including hundreds of articles in WoS journals. In light of the increasing teacher shortages, both teacher educators and education researchers require insights that can identify potential areas for collaboration.

Bibliometric studies have already proven to be a significant contribution in themes of teacher education, such as leadership and professional teacher learning (Hallinger & Kulophas, 2019), classroom dialogue (Song et al., 2019), or inclusive education in initial teacher training (Cretu & Morandau, 2020). Also, significant contributions have been made to the understanding of research frameworks through bibliometric analyses in science education and mathematics education (Gil-Doménech et al., 2020; Kadirhanoğulları & Köse, 2024; Özkaya, 2018). In all these cases, under-researched areas have been identified, and future research lines have been projected.

Based on this background, the research question addressed was: What are the main trends in PCK research across different areas of knowledge from 1986 to the present? Similarly, the objective was to identify productivity trends in PCK across various fields of knowledge through a bibliometric analysis using classic coefficients and the VOSviewer program, based on journals from the WoS database.

METHODS

Given the importance of using nomological networks in bibliometric analyses, a tool like VOSviewer is essential. However, VOSviewer's main limitation lies in its compatibility with export files from only a single bibliographic database, as different databases organize their fields and metadata differently. Whether increasing the number of databases affects bibliometric results has shown mixed evidence. While some comparative studies report significant variations when analyses are repeated with different databases (Mongeon & Paul-Hus, 2016), others suggest similar outcomes (Belew, 2005) or high correlations between bibliometric indices (Archambault et al., 2009).

In this study, we selected Web of Science (WoS) as our preferred database for its selectivity and advanced tools such as Journal Citation Reports (Pranckutė, 2021). However, WoS has faced criticism for its lack of transparency in journal inclusion processes and potential biases as a commercial entity (Masic et al., 2022). These limitations can result in the exclusion of high-quality journals and the inclusion of others with questionable standards. Despite these challenges, WoS remains a widely used and valuable resource for bibliometric analyses due to its robust tools and broad acceptance in academic research.

A set of articles with equivalent indexing data was used, prioritizing the quality of journals in the core collection from the WoS. Only articles and reviews were selected based on a search string for "Pedagogical Content Knowledge" (TS = Pedagogical NEAR/0 content NEAR/0 knowledge), which was queried using the advanced search module of WoS. No temporal restrictions were applied (although the natural limit was 1986, following Shulman's (1986) seminal article), and the extraction was performed on March 9, 2023. The advanced search field tag TS (topic) searches for a thematic term in the following fields within a record: title, abstract, author keywords, and keywords plus®. The search for relevant articles was facilitated by the fact that the construct is not polysemous and is exclusively used in the context of educator training.

A bibliometric analysis was conducted on a set of articles obtained for the study topic using five fundamental bibliometric laws, in two phases:

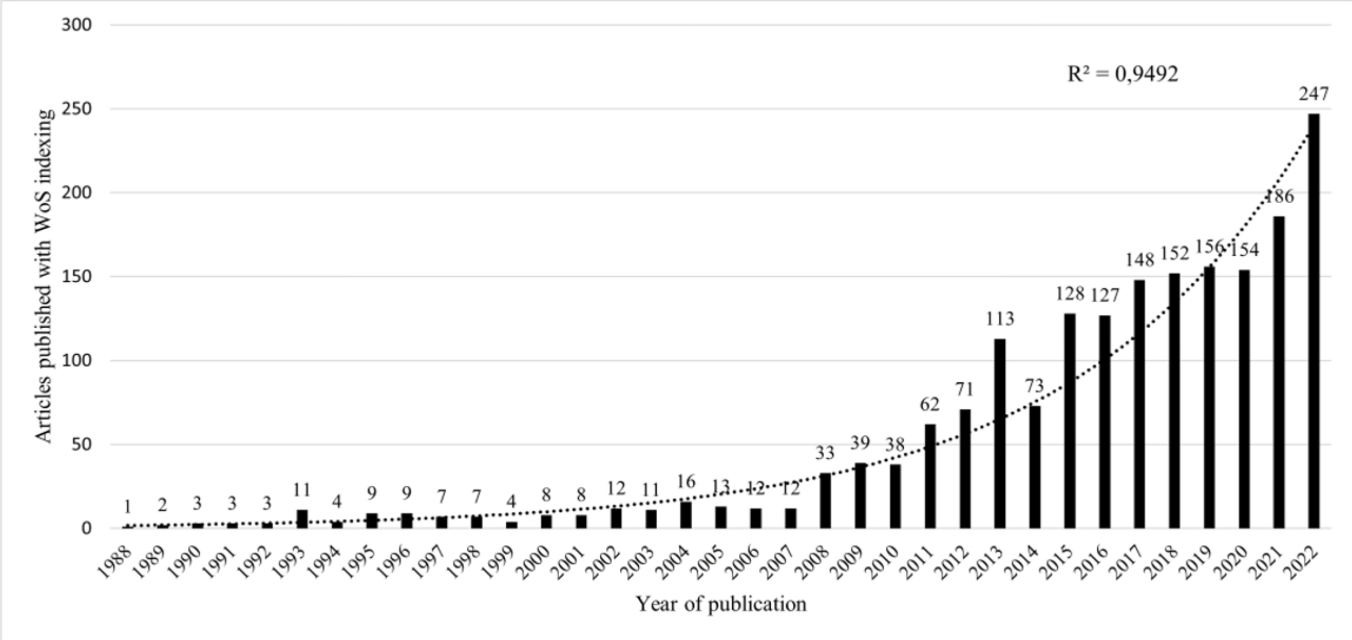

Figure 1. Publications on "PCK" between 1988 and 2022: The bars correspond to the data series showing the annual number of publications, and the dashed line represents the exponential trendline (Source: Authors' own elaboration)

Phase 1. Bibliometric Analysis of Scientific Production

1. Exponential growth of research or Price's (1976) law: The annual growth of publications (in this case, articles published per year) was analyzed for exponential growth using the coefficient of determination (R^2) of the exponential trend line fitted in Microsoft Excel. This calculation served as a measure of the scientific community's interest in the construct, confirming an exponential increase in publications in the area.
2. Publication concentration according to authors or Lotka's law: Recognizing that in any field of knowledge, the majority of articles come from a small proportion of prolific authors, identified and studied individually by estimating the square root of the total number of authors. This verification is done through the power law fit using the trend line in Microsoft Excel between publishing authors and published articles, assessed by the R^2 (Coile, 1977).
3. Hirsch index (h-index): This index specifies a set of "n" articles that have each received "n" or more citations. It is determined by the intersection of the ordered pairs of the number of citations received by each published article (in decreasing order) and the cumulative count of published articles. Cross-citation analysis observes the citation network among a specific set of articles, highlighting how some articles serve as the basis for creating new knowledge (Hirsch, 2005; Sainaghi et al., 2018).

Phase 2. Bibliometric Analysis of Scientific Production Areas

1. Publication concentration in journals or Bradford's law: Journals were distributed into thirds based on the decreasing number of documents published in them, establishing a core of journals with the highest concentration, covering at least 33% of the total published records (in this case, published articles) (Bulick, 1978; Morse & Leimkuhler, 1979).
2. Keyword concentration or Zipf's law: This involves identifying the most frequently used keywords in the set of articles, estimated by the square root of the total number of words. This was verified by fitting a power law trend line in Microsoft Excel between the frequency of keywords plus (KWP) and the number of published articles, using the R^2 (Zipf, 1932).

Finally, VOSviewer software was used for data processing and visualization, including co-occurrence analysis and visualization clustering. This analysis identified solo authors, author dyads, author triads, and clusters of these, countries producing collaboratively or autonomously, and thematic clusters (Perianes-Rodriguez et al., 2016; Waltman et al., 2010).

RESULTS

A total of 1,942 articles were identified using search parameters, spanning publications from 1988 to 2022. The earliest article is "Teachers' pedagogical content knowledge of students' problem-solving in elementary arithmetic," published in the Journal for Research in

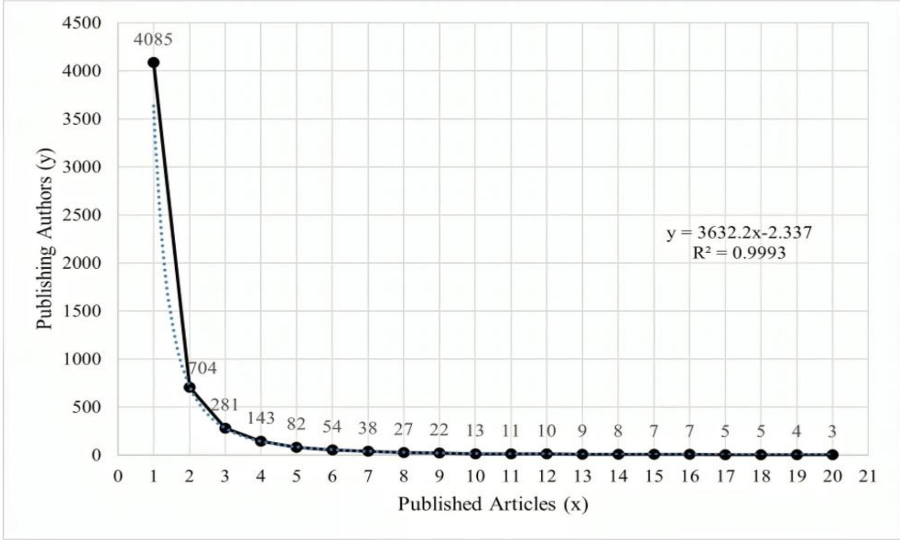

Figure 2. Graph of the relationship between scientific production level and authors (Source: Authors' own elaboration)

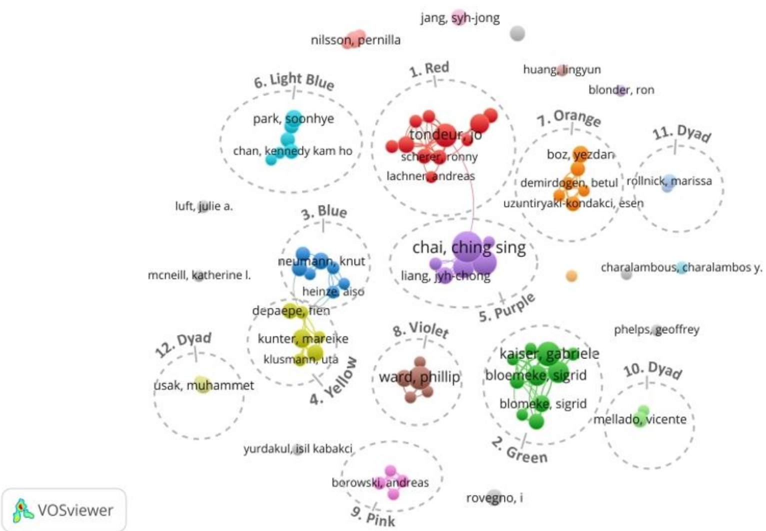

Figure 3. Nomological network showing clusters identified using VOSviewer when visualizing groups of researchers who are co-authors of articles on PCK with a minimum of 6 publications (Source: Authors' own elaboration, using VOSviewer)

Mathematics Education shortly after Shulman's (1986, 1987) seminal articles in 1986 and 1987. By 2003, only about 100 articles on 'PCK' had been published. By 2009, this number had doubled. Thereafter, a sustained increase was observed, culminating in 247 articles published in 2022 alone (**Figure 1**).

We analyzed the exponential growth of publications during this period, yielding robust results (with an R^2 of nearly 95%). Articles published in 2023 (n = 88) were not considered, as the search was conducted early in the year. The increase in PCK studies indexed in WoS journals supports the feasibility of bibliometric analysis.

Results of Scientific Productivity in Relation

The number of authors who contributed knowledge through the 1,942 analyzed articles was 4,085 (extracted using VOSviewer from the "full author name" field of each record). Most of these authors contributed to only one article, as shown in **Figure 2**, which illustrates the distribution of authors' productivity levels based on the number of articles they have published. It is important to note that the total number of articles is 1,942, and that 4085 different authors have participated in at least one of these articles. According to Lotka's law, the number of authors with the highest contribution is estimated at 63 (the square root of 4,085). In this study, we defined a prolific author as one who has published 6 articles on PCK. This threshold was not chosen arbitrarily; rather, it was determined by seeking the closest match to the value predicted by Lotka's law. Among the data analyzed, 54 authors meet this criterion, aligning closely with the estimated 63. The alternative thresholds were 82 authors with 5 articles or 38 authors with 7 articles (**Figure 2**), but these numbers deviated more significantly from Lotka's estimate. This rationale ensures a balance between empirical evidence and theoretical expectations.

Table 1. List of authors with at least 6 articles published on PCK grouped into clusters and dyads

Cluster PCK domain	Authors	Articles	Citations	ACs	Links	TLS	Country
1. Red, TPACK	Tondeur, J.	19	1,205	63	8	32	Belgium
	Voogt, J.	13	699	54	3	11	Netherlands
	Baran, E.	10	426	43	6	13	United States
	Scherer, R.	7	670	96	7	20	Norway
	Siddiq, F.	7	670	96	7	20	Norway
	Mckenney, S.	7	202	29	1	4	Netherlands
	Sointu, E.	6	162	27	5	12	Finland
	Valtonen, T.	6	162	27	5	12	Finland
	Chuang, H.-H.	6	88	15	1	1	Taiwan
2. Green, math	Bloemeke, S.	23	676	29	14	54	Norway
	Kaiser, G.	20	510	26	7	42	Germany
	Köenig, J.	16	472	30	7	31	Germany
	Jenssen, L.	8	77	10	4	14	Germany
	Suhl, U.	7	311	44	8	21	Germany
	Yang, X.	6	63	11	3	12	China
3. Blue, math sci	Heinze, A.	6	77	13	5	8	Germany
	Neumann, K.	9	155	17	6	11	Germany
	Harms, U.	8	136	17	4	6	Germany
	Kind, V.	7	375	54	2	2	United Kingdom
	Sorge, S.	6	36	6	4	9	Germany
4. Yellow, math	Kunter, M.	12	2,218	185	5	21	Germany
	Baumert, J.	9	2,166	241	4	19	Germany
	Depaepe, F.	8	112	14	1	1	Belgium
	Kleickmann, T.	6	327	55	6	10	Germany
	Klusmann, U.	6	1,514	252	3	10	Germany
5. Purple, TPACK sci	Chai, C. S.	33	1,402	42	6	35	Hong Kong
	Hsu, C.-Y.	6	93	16	3	8	Taiwan
	Koh, J. H. L.	22	1,057	48	4	26	New Zealand
	Liang, J.-C.	9	128	14	4	14	Taiwan
	Tsai, C.-C.	16	1,014	63	5	26	Taiwan
6. Light blue, sci	Chan, K. K. H.	7	93	13	2	2	Hong Kong
	Neuhaus, B.	7	194	28	2	2	Germany
	Park, S.	11	887	81	1	1	United States
	van Driel, J.	13	763	59	3	5	Australia
	Nilsson, P.	10	323	32	2	2	Sweden
	Walan, S.	6	13	2	1	1	Sweden
7. Orange, sci	Boz, Y.	9	116	13	1	3	Turkey
	Demirdogen, B.	6	113	19	4	14	Turkey
	Uzuntiryaki-Kondakci, E.	7	104	15	4	11	Turkey
	Aydin, S.	7	143	20	5	12	Turkey
8. Violet, PE	Ward, P.	18	474	26	4	20	United States
	Kim, I.	9	213	24	4	13	United States
9. Pink, sci	Borowski, A.	6	65	11	3	12	Germany
	Riese, J.	6	94	16	3	14	Germany
10. Dyad, sci	Mellado, V.	8	219	27	1	5	Spain
11. Dyad, sci	Rollnick, M.	7	194	28	1	1	South Africa
12. Dyad, sci	Usak, M.	9	100	11	1	1	Russia

Note. AC: Average citations & TLS: Total link strength

By utilizing author group analysis based on co-authorship of articles, VOSviewer identified a total of 12 clusters, out of which 9 consisted of groups with at least 4 authors. In **Figure 3**, the 12 clusters can be identified, along with the prolific members of each cluster, as well as the names of other prolific researchers who lead teams without forming a cluster.

Complementary to the nomological map shown in **Figure 3**, **Table 1** lists authors with at least 6 articles published on PCK, belonging to one of the 9 identified clusters, along with 3 dyads. These clusters and dyads generally represent geographical and thematic associations related to the studied PCK domain. Specifically, two clusters (red and purple) concentrate articles and citations on TPACK, one consisting of

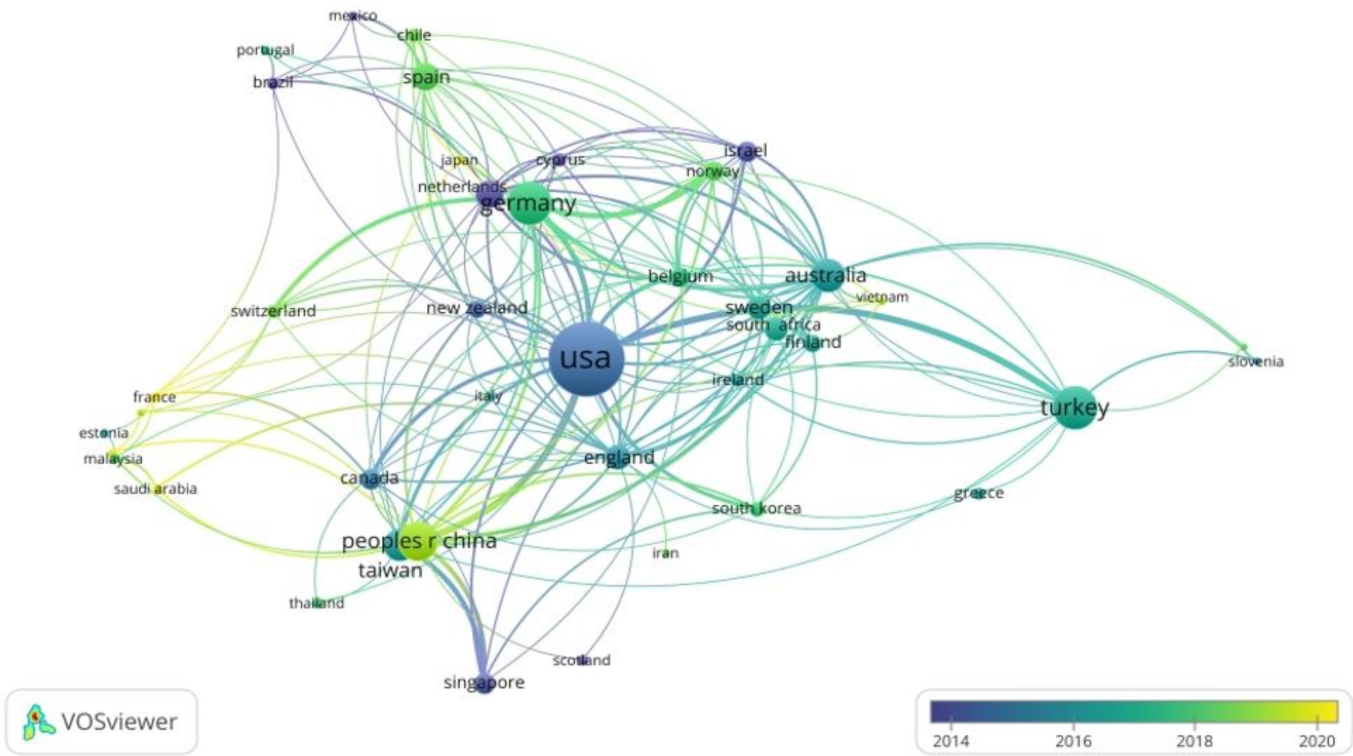

Figure 4. Visualization of countries with highest productivity, colored by average publication years (Source: Authors' own elaboration, using VOSviewer)

researchers primarily from Nordic affiliations and another from Asia-Pacific countries. Two clusters (green and yellow) focus on mathematics PCK and are primarily affiliated with German universities. Interestingly, co-authorships between these two clusters are almost nonexistent. There are four clusters specializing in science PCK: two involve researchers with German affiliations, one is Turkish, and another is more internationally diverse. A single small cluster specializes in physical education, which also represents the only cluster from the United States. The three dyads are from researchers in science PCK corresponding to Spain, South Africa, and Russia. No clusters specialized in other PCK domains are evident. In practice, the majority of researchers leading PCK publications specialize in science PCK, followed by TPACK and mathematics. In terms of groupings, there is no representation from Latin America

Results by Country

Partially consistent with the cluster analysis described the countries with the highest productivity are the United States (n = 601), Germany (n = 203), Turkey (n = 201), China (n = 167), Australia (n = 123), Taiwan (n = 109), the Netherlands (n = 88), and Spain (n = 82). The nomological network in **Figure 4** focuses on the countries of affiliation declared by the authors of the analyzed articles, highlighting international scientific collaborations. The lines connecting the countries represent co-authorship relationships, where the thickness of each line indicates the frequency or intensity of collaboration. The color gradient of the lines reflects the average year of these collaborations, with darker blue tones corresponding to earlier collaborations (around 2014) and lighter green-yellow tones representing more recent connections (up to 2020). Countries such as the United States, Germany, and China stand out as central nodes with a high volume of international collaborations, while other countries, like Turkey and Australia, also emerge as relevant hubs with extensive connections to multiple regions. This visualization reveals both the density and evolution of global research networks. Countries like China, Taiwan, Australia, Turkey, and Germany have achieved leadership in the last 5 years, while others such as Singapore, Israel, and the Netherlands tend to show decreasing productivity. Several countries, although not associated with clusters, demonstrate emerging productivity, such as Norway, Belgium, South Korea, and Chile. On the other hand, it is noteworthy that countries with high overall productivity in educational topics appear underrepresented, as is the case with England, France, and Finland.

Regarding the 14 most prolific authors (10 publications or more), there are three representatives from Germany and three from the United States, being the only two countries that repeat (see **Table 1**). The others are from Northern European countries (Sweden, Norway, the Netherlands, and Belgium) and the Asia-Pacific region (Hong Kong, Taiwan, and New Zealand). Thus, in general, these authors belong to countries with

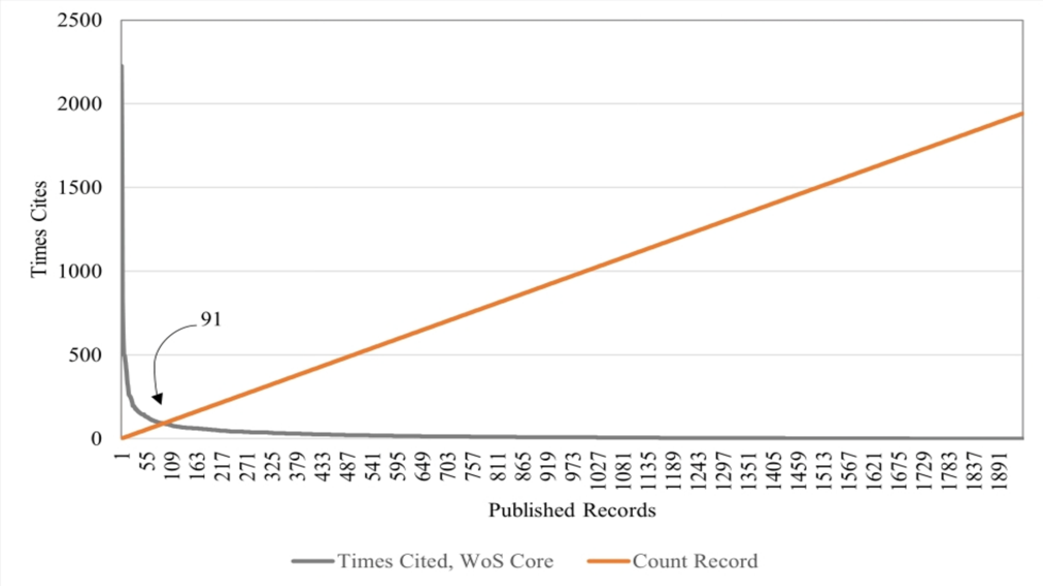

Figure 5. Calculation of the h-index (Source: Authors' own elaboration)

the highest productivity. Although the United States contributes 601 articles (approximately 30% of the total 1942 articles in the bibliometric study), it is particularly interesting that, despite having three prolific authors, they do not form or belong to their own cluster. This suggests that much of this productivity comes from independent authors or those whose primary research focus is not PCK.

For a deeper analysis of the role and interaction between prolific authors and highly productive countries in PCK studies, we incorporated the Hirsch index, or h-index as a factor to weigh the impact of these 47 authors and 17 countries/territories. **Figure 5** shows the calculation of the h-index, with 91 articles having 92 or more citations. These 91 articles categorized by PCK domain can be reviewed and reveal some specific trends: The most cited articles do not strictly correspond to the most prolific authors. Considering the total, only 28 were written by prolific authors, which is 31%. Among the 12 articles with over 400 citations (the average citation count of the 91 articles is 232), only 5 belong to prolific authors. 48% of the 91 most cited articles belong to researchers affiliated with the United States. The next countries are Germany (8%), Netherlands (7%), Australia (6%), Taiwan (5%), and United Kingdom (4%). This proportion does not align with what was observed in the clusters. In a way, researchers from the US universities (similar to Shulman's, 1986, 1987 influence) have had a significant impact on PCK research, despite not belonging to any specialist groups. 80% of the most cited articles were published between 2004 and 2014, peaking in 2011 (15 articles). 80% of the most cited articles were published in 16 journals, with Computers & Education (14%), Journal of Research in Science Teaching (12%), International Journal of Science Education (9%), Journal of Teacher Education (5%), and Research in Science Education (5%) being the most frequent. These are generally specialized journals in specific educational areas (TPACK, sciences, or mathematics) or focused on teacher education research.

To evaluate whether the most prolific authors are also responsible for the most highly cited WoS articles in each PCK domain, a Venn diagram was constructed comparing authors with high productivity (6 articles or more) with authors of the most cited articles in WoS, categorized into PCK domains (mathematics, sciences, TPACK, and others) (**Figure 6**). The diagram shows that only a portion of authors is shared between both categories, indicating a large volume of research not originating from the authors with most publications. Henceforth, these authors will be referred to as "key authors". This pattern repeats across different PCK domains. A systematic review should possibly consider both groups of authors.

Results of the Scientific Production Space

The 1,942 articles in the review were published in a total of 297 different journals, of which 128 (43%) include only one article on PCK, indicating that these are not specialized publications. According to Bradford's law, one-third of the articles (641, 33% of the total) are concentrated in only 11 journals, which correspond to the core publications on PCK, as detailed in **Table 2**.

It is interesting to note that only 11 journals (4% of the total journals) concentrate one-third of the PCK articles. Moreover, five of these publications specialize in science education and three in technology education. This trend was not observed in previous analyses and seems to indicate that journals specializing in science and technology education represent a specific niche for PCK research. This may also be associated with the fact that there are more journals in mathematics education in

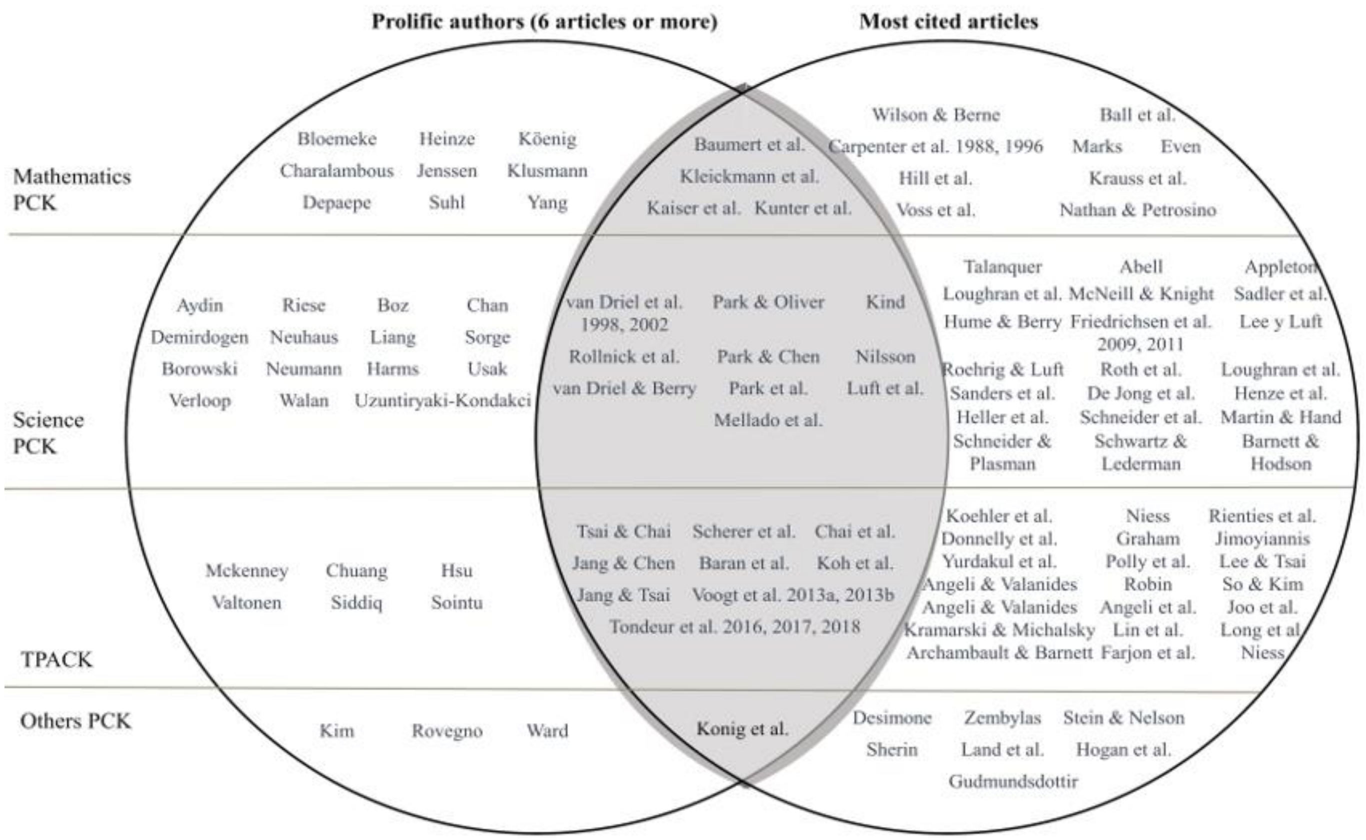

Figure 6. Venn diagram showing overlaps between prolific authors and authors of the most cited articles (Source: Authors' own elaboration)

Table 2. Main journals publishing about PCK (32 or more articles)

Core Bradford Journal	Publisher	WoS index	IF (2022)	BQ	n
Teaching and Teacher Education	Pergamon-Elsevier Science Ltd.	SSCI	3.9	Q1	101
International Journal of Science Education	Taylor & Francis Ltd.	SSCI	2.3	Q1	85
Research in Science Education	Kluwer Academic Publications	SSCI	2.3	Q1	69
Chemistry Education Research and Practice	Royal Society Chemistry	SSCI & SCIE	3.0	Q1	61
Journal of Research in Science Teaching	Wiley-Blackwell	SSCI	4.6	Q1	59
Computers & Education	Pergamon-Elsevier Science Ltd.	SSCI, SCIE	12.0	Q1	58
International Journal of Science and Mathematics Education	Springer	SSCI	2.2	Q2	48
Journal of Teaching in Physical Education	Human Kinetics Publication, Inc.	SSCI & SCIE	2.8	Q1	45
Australasian Journal of Educational Technology	ASCILITE	SSCI	4.1	Q1	42
Education and Information Technologies	Springer	SSCI	5.5	Q1	41
Frontiers in Psychology	Frontiers Media SA	SSCI	3.8	Q1	32
Total					641

Note. SCIE: Science Citation Index Expanded; SSCI: Social Science Citation Index; IF: Impact factor; BQ: Best quartile; & n: Number of articles

general, making it harder for any to focus specifically on this topic.

In general, as shown in **Table 2**, the journal that concentrates the most articles is *Teaching and Teacher Education*, published by Pergamon-Elsevier Science Ltd., with 101 articles. At the publishing level, Pergamon-Elsevier Science Ltd. is the publisher that concentrates the most publications (n = 159), followed by Springer (n = 89) and Taylor & Francis Ltd. (n = 85).

The 11 journals can be considered mainstream as they are indexed in SSCI (some in SCIE), and almost all are in the Q1 quartile, even though only four of them have an impact factor greater than 4. In this sense, *Computers & Education* stands out as an outlier with an IF of 12, far above the others. Practically speaking, it can be affirmed that the core journals on PCK have high impact, prestige, and reach a large international audience.

The patterns recognized by area in several of the previous analyses are also evident at the level of keywords. To illustrate this, the total number of WoS Plus keywords from the 1,942 articles was considered, totaling 1,573 different keywords. According to Zipf's

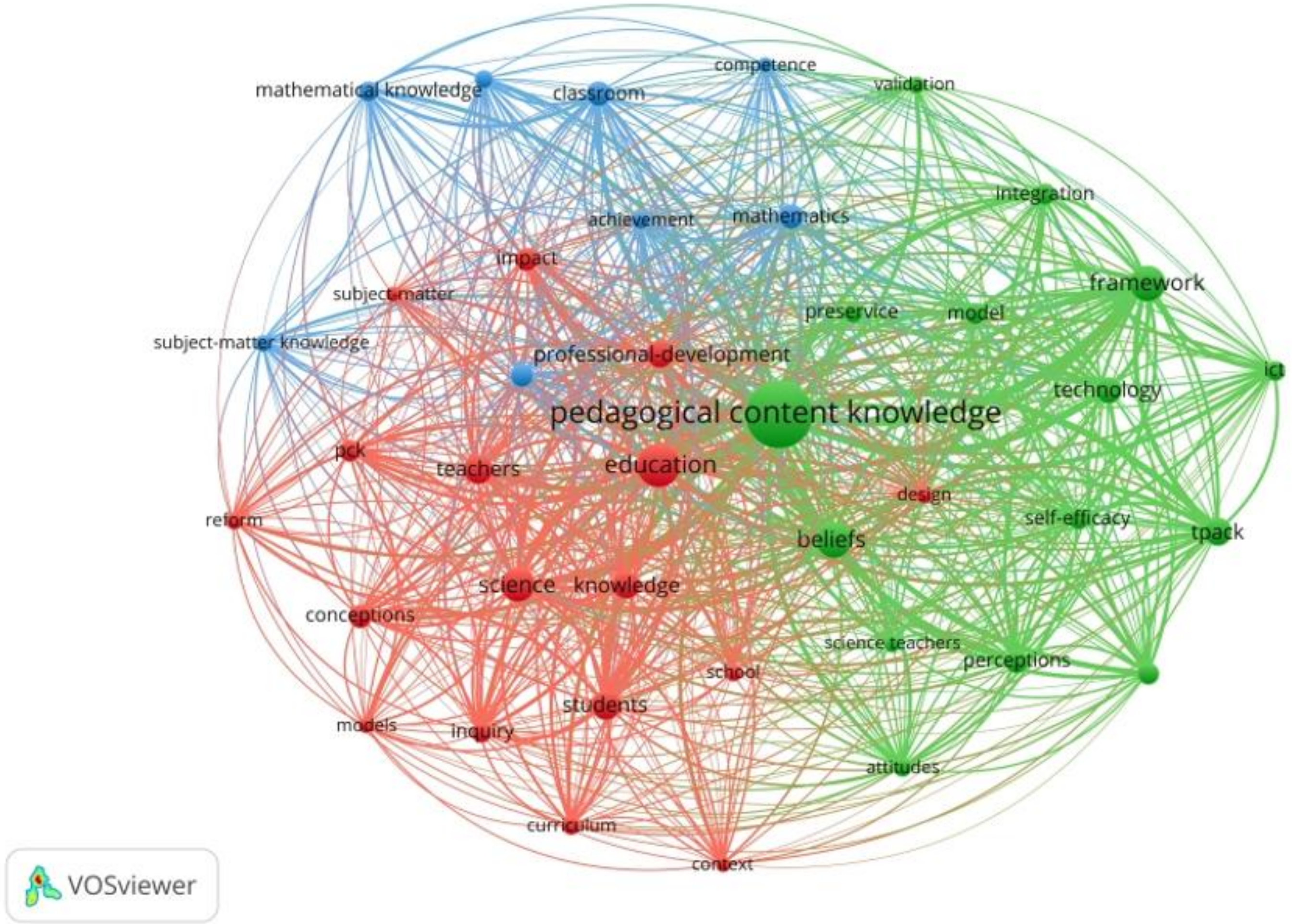

Figure 7. Co-occurrence diagram of the 40 most common plus keywords from the analyzed articles (Source: Authors' own elaboration, using VOSviewer)

law, in a large set of words, some are used much more frequently than others, and this frequency follows an inverse distribution pattern, where the most common word appears approximately twice as often as the second most common word, three times as often as the third, and so on. According to this rule, the number of most common words is estimated by calculating the square root of the total number of words, which is 40 keywords (square root of 1,573). With this starting point, a co-occurrence diagram was created using VOSviewer, showing the 40 most common keywords from the total articles, organized in a network of between 40 and 924 occurrences (**Figure 7**).

According to the diagram in **Figure 7**, three clusters of keywords are identified. The red cluster represents words associated with science PCK, highlighting terms such as conceptions and inquiry, typical of specific didactics. The blue cluster represents a network around mathematics PCK, where terms like achievement and competence are closely associated with mathematical knowledge and similar terms. Finally, the green cluster includes terms associated with technology PCK or TPACK, with terms like theoretical framework, beliefs, and integration standing out.

Although the analysis of clusters–such as those of authors, journals, and keywords–primarily highlights studies on TPACK, science PCK, and mathematics PCK, there is a small group of authors and articles from other disciplines, such as language education (including English as a second language), physical education, and general PCK research that do not focus on a specific subject area. These works, although less prominent in broader literature, appear to be influential within their respective fields, as illustrated in **Figure 6**.

These trends suggest the need to foster interdisciplinary spaces for academic dialogue, where the specific insights from each field can converge and enrich the broader understanding of PCK. For instance, a collaborative study between science and mathematics educators could examine how inquiry-based approaches in science education–such as designing experiments or analyzing environmental data–might be adapted to enhance problem-solving and data interpretation skills in mathematics education. This type of cross-disciplinary collaboration could provide new strategies to address shared challenges in teaching abstract concepts or fostering critical thinking.

DISCUSSION

The productivity on PCK facilitated a robust bibliometric analysis based on 1,942 WoS articles. The sustained increase in the number of publications on this subject confirms the need for this initial bibliometric analysis, almost 40 years after Shulman (1986) coined the term.

Bibliometric studies in PCK have concentrated on a limited period (Alka et al. 2023; Ye et al. 2019). The exception is the bibliometric review by Doğru et al. (2019), Turkish authors who also considered the WoS database for the period 1970-2019 (which is surprising, considering the year of publication of Shulman's (1986) original works). Although their study coincides with some of the findings of this bibliometric analysis, it does not present basic bibliometric indices, nor does it rely on visualization software that facilitates the identification of clusters and derived patterns.

In general, more significant contributions have come from systematic reviews, which have focused on PCKs in specific domains: sciences (Abell, 2008; Chan & Hume 2019; van Driel et al., 2023); mathematics (Depaepe et al. 2013); history (Tuithof et al., 2023); physical education (Ward & Ayvazo, 2016), geography (Smit et al., 2023), or in different educative topics: higher education (Sarkar et al., 2024), specific models (Mientus et al., 2022), or PCK as a general construct (Berry et al., 2016).

The value of a bibliometric analysis like this is that it allows us to identify the complete history of scientific production on PCK, recognize geographical and domain trends, co-authorship clusters, journals, keywords, and the most prominent authors. Additionally, the use of visualization software allows us to understand the temporal scale in which advances are made and to identify emerging leaders and research areas that currently occupy specialists the most.

The increase in PCK research is exponential, as seen in similar bibliometrics (Alka et al., 2023; Irwanto, 2021; Nasir et al., 2023). Most of the PCK researchers who have published in WoS-indexed journals have only participated in a few publications, with a rather small number of specialists (< 100) having published 6 studies or more. These specialists are mostly associated with other researchers addressing the same specific PCK, with few or no connections between clusters. While bibliometric analyses on PCK have identified limited clusters (Alka et al., 2023; Doğru et al., 2019), this would be the first time they are linked to a specific number of publications, identifying the countries and disciplinary areas that characterize each cluster.

Bibliometric reviews indicate that the countries with the highest productivity in education studies are invariably the United States, China, the United Kingdom, Turkey, and Australia (Maral, 2024; Özkaya, 2018). This result is partially consistent with ours, where Germany, the Netherlands, Spain, and Taiwan show significant leadership, even surpassing the United Kingdom, which, although it shows considerable productivity, does not seem to have the same presence as in other bibliometrics in education. One might wonder whether the low profile of the United Kingdom or other European countries, which typically have many publications in education, such as France or Finland, is due to the fact that the topic of professional knowledge of teachers is not addressed from the PCK construct or if there is indeed a lower volume of researchers interested in studying teachers' professional knowledge.

The present bibliometric analysis enables us to describe asymmetries in productivity, both geographically and in the domains of PCK. The latter is especially relevant since it is a construct that, without being "adopted" by any particular domain, has developed in parallel paths with little communication between domains and with surprisingly unequal levels of productivity. This occurs even though most teachers trained worldwide are not trained in a specific domain but in the context of primary education teacher preparation, where they must achieve competence in PCK in multiple disciplines simultaneously. At the same time, among PCK researchers, whether prolific or not, almost none investigate more than one domain.

As seen in the review, most PCK research is concentrated in mathematics and sciences. While there are some reviews that address PCK in general, alluding to this phenomenon (Berry et al., 2016), the question of the concentration of PCK in only two areas has hardly been addressed. Cooper and van Driel (2019) point out that the problem originates in the way research on teacher education is currently communicated and disseminated. Both journals and conferences are domain-specific, so PCK specialists only meet and discuss among themselves, hindering the exchange of advances on this common construct. This concentration of PCK research in STEM subjects could be partly explained by the perceived difficulty of these disciplines, which often leads to lower student performance and greater pedagogical challenges for teachers. In response, researchers and educators in these fields may have prioritized PCK studies as a way to better understand and improve teaching practices, ultimately seeking to address the reputation of these subjects as particularly challenging for students (Bogdan, 2022; Valero-Matas and Coca, 2021). This interpretation aligns with the notion that teacher education research is often driven by immediate needs and perceived barriers in specific domains (Sleeter, 2014).

An equally necessary aspect to address is the lack of research and development in some domains, specifically in history, language, foreign language, philosophy, visual arts, and music. These are all areas with a long tradition in teacher education and teacher training research, yet there seems to be little interest in incorporating the PCK dimension. Do they use an equivalent construct, perhaps a previous one about teacher knowledge? Are these domains where professional knowledge is organized differently, making PCK less relevant? Do they know the main uses or characteristics pertaining to PCK in their domains? Or perhaps it is a more practical problem: Is it a construct that their specialists are just discovering, given the limitations noted by Cooper and van Driel (2019) for exchanging knowledge about teacher education in different domains?

Shulman (1986, 1987) originated a construct that has given rise to thousands of research projects and a concerted effort by researchers worldwide to systematize the knowledge required to become a teacher. Shulman's (1986, 1987) two initial articles are among the most cited studies in the history of teacher education (Ananin & Lovakov, 2022), and the PCK-derived models have allowed us to understand the progression towards high-quality teaching. Moreover, it is a construct that positions and elevates the teaching profession by providing it with a theoretical framework distinct from the disciplinary content being taught, which should lead to a more prominent use of it.

Such purposes cannot belong to some disciplinary domains and not others. If we do not fully agree on what the foundational knowledge required to teach any disciplinary area is, how can a curriculum or study plan for training teachers in such areas be established? Shulman (2015) has questioned the validity of the specificity of classic disciplinary domains, and PCK findings in one area seem to naturally enrich other domains (Berry et al., 2016).

The trend of new curricula and standards is interdisciplinary work, with a decreasing conceptual load in traditional subjects, as the focus seems to be on problem-solving and project development (Drake & Reid 2020; Infante-Malachias & Araya-Crisóstomo 2023). In this sense, it seems that the future of PCK could be more integrative, as shown by studies less focused on closed topics and more on cross-cutting or procedural themes such as the PCK of argumentation (e.g., McNeill et al., 2016; Larraín et al., 2022) or the PCK of critical thinking (Ab Kadir, 2017).

In their review, Berry et al. (2016) present a series of findings on the nature of the construct, its measurement, and its implications for teacher education, which are particularly relevant across disciplines such as mathematics, science, languages, geography, and physical education. For instance, researchers in mathematics teacher education have applied the refined consensus PCK model developed for science PCK (van der Jagt & Nielsen, 2024).

The search for greater symmetry should also be pursued in geographical and cultural domains. Shulman (2015) highlighted that one of the weaknesses of the construct was not paying attention to this aspect: 'Culture and context are broad environments within which we find many of the determinants of teaching and learning' (p. 9). The PCK we have today derived from studies done fundamentally in the United States and European scenarios, as is the case with most research topics in science education, that found the scholarly contributions of Latin American and African researchers to the international community were relatively small throughout the years (Medina-Jerez, 2018; Wang et al., 2023). However, this work has highlighted the emergence of several groups in different parts of the world researching PCK in science, mathematics, and technology.

How does it manifest in vulnerable environments or with teachers who did not train at prestigious universities? Can any teacher use PCK in any given diverse context? For example, in Chile, there are research groups working on PCK of evolution, where their studies have shown many similarities with research conducted in the United States and Europe (e.g., the importance of preconceptions such as the idea of necessity, teaching strategies like argumentation), but also some important differences (e.g., less concern for the religious beliefs of the community; the challenge of teaching evolution before inheritance) (Becerra et al., 2023; Bravo & Cofré, 2016; Ravanal Moreno et al., 2024; Vergara et al., 2024). The same happens in Brazil, where studies on PCK highlight the relevance of collaborative groups to promote discussions, reflections, and the exchange of practical experiences, which contrasts with more individualized approaches observed in research from the Northern Hemisphere (Albieri de Almeida et al., 2019), or in South Korea, where science teachers tend to address students' alternative ideas more explicitly than US teachers (Park et al., 2020). The productivity gap between Europe, North America, and developing countries has been widely documented (Holmgren & Schnitzer, 2004), and PCK does not seem to be the exception. However, as shown in our study, there may be several countries that could make important contributions.

It would be very interesting to generate comparative studies of PCK on the same topics (e.g., genetics, geometry, writing) but in different countries or continents, similar to the approach of Park et al. (2020). This bibliometric study provides a directory of countries with emerging and valuable research, whose authors could be welcomed by the established groups of the Northern Hemisphere.

CONCLUSIONS

The present bibliometric analysis identified several trends related to PCK productivity across various fields of knowledge. Since the term was coined, the topic has received exponential research coverage (R^2~95%), which has fostered a progressive understanding of the knowledge inherent in teaching practice. Despite this growth, the number of specialized authors who have published recurrently (6 times or more in WoS journals) is relatively small (n = 54), and they tend to group into clusters related to the PCK domain and geographical areas. The countries leading current PCK publications are the United States, Germany, Turkey, China, Australia, and Taiwan, although the latter five have achieved this leadership more recently. Indeed, researchers affiliated with U.S. universities have had a significant influence on PCK research, despite not belonging to any of the high productivity specialist clusters.

A list of key PCK authors was defined, considering the number of published articles (n = 6) and having been the primary author in one of the most cited articles (according to the Hirsch index). This list only represents the areas of mathematics, science, and TPACK, where all authors are associated with a single domain. Additionally, the journals in which they publish are also domain-specific, hindering the transfer of findings between domains. The core PCK journals (32 or more articles) are highly impactful, prestigious, and reach a large international audience. However, key authors prefer journals aimed at researchers in their own field, promoting domain endogamy. Similarly, the most common keywords are domain-specific, suggesting that each area of PCK research has its own unique richness and complexity. However, the boundaries between these domains remain unclear, as many terms transcend disciplinary lines.

Implications

The identified trends suggest new areas of study: First, it seems sensible to identify the areas where PCK research developments converge and diverge between domains, as a means of defining transferable knowledge. Regarding the developed models, it is important to assess the coherence between the PCK models defined in each domain and the authors' interest in using them as reference frameworks. Additionally, it is crucial to understand the alternative theoretical frameworks on professional teaching knowledge used by the less represented domains in this bibliometric study, and whether the greater development of PCK research in certain countries is related to the incorporation of these findings into public policy and their eventual relationship with learning outcomes. In a related perspective, it is essential to delve into the relationship between PCK research asymmetry across domains and the perceived complexity of teaching and learning in science and mathematics compared to other fields. Lastly, from a more global perspective, we propose to address the nature of PCK research in the Southern Hemisphere or Middle East countries that have not participated in defining the most influential PCK models but may have interesting perspectives to contribute.

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REFERENCES

Ab Kadir, M. A. (2017). What teacher knowledge matters in effectively developing critical thinkers in the 21st century curriculum? *Thinking Skills and Creativity, 23*, 79-90. https://doi.org/10.1016/j.tsc.2016.10.011

Abell, S. K. (2008). Twenty years later: Does pedagogical content knowledge remain a useful idea? *International Journal of Science Education, 30*(10), 1405-1416. https://doi.org/10.1080/09500690802187041

Albieri de Almeida, P. C. A. D., Davis, C. L. F., Calil, A. M. G. C., & Vilalva, A. M. (2019). Shulman's theoretical categories: An integrative review in the field of teacher education. *Cadernos de Pesquisa, 49*, 130-149. https://doi.org/10.1590/198053146654

Alka, M., Bancong, H., & Muzaini, M. (2023). Bibliometric analysis of pedagogical content knowledge (PCK) publication trends in Scopus Database from 2018 to 2022. *Studies in Learning and Teaching, 4*(2), 306-318. https://doi.org/10.46627/silet.v4i2.222

Alonzo, A. C., Kobarg, M., & Seidel, T. (2012). Pedagogical content knowledge as reflected in teacher-student interactions: Analysis of two video cases. *Journal of Research in Science Teaching, 49*(10), 1211-1239. https://doi.org/10.1002/tea.21055

Alvariñas-Villaverde, M., Domínguez-Alonso, J., Pumares-Lavandeira, L., & Portela-Pino, I. (2022). Initial motivations for choosing teaching as a career. *Frontiers in Psychology, 13*, Article 842557. https://doi.org/10.3389/fpsyg.2022.842557

Ambrose, V. K., Davis, C. A., & Ziegler, M. F. (2013). From research to practice: A framework for contextualizing teaching and learning. *Journal of College Reading and Learning, 44*(1), 35-50. https://doi.org/10.1080/10790195.2013.10850371

Ananin, D., & Lovakov, A. (2022). Teacher education research in the global dimension: Bibliometric perspective. *Teaching and Teacher Education, 118*, Article 103801. https://doi.org/10.1016/j.tate.2022.103801

Appleton, K. (2006). Science pedagogical content knowledge and elementary school teachers. In K. Appleton (Ed.), *Elementary science teacher education: International perspectives on contemporary issues and practice*. Lawrence Erlbaum Associates. https://doi.org/10.4324/9781315045443-4

Archambault, É., Campbell, D., Gingras, Y., & Larivière, V. (2009). Comparing bibliometric statistics obtained from the Web of Science and Scopus. *Journal of the American Society for Information Science and Technology, 60*(7), 1320-1326. https://doi.org/10.1002/asi.21062

Baxter, J. A., & Lederman, N. G. (1999). Assessment and measurement of pedagogical content knowledge. In J. Gess-Newsome, & N. G. Lederman (Eds.), *Examining pedagogical content knowledge: The construct and its implications for science education* (pp. 147-161). Springer. https://doi.org/10.1007/0-306-47217-1_6

Becerra, B., Núñez, P., Vergara, C., Santibáñez, D., Krüger, D., & Cofré, H. (2023). Developing an instrument to assess pedagogical content knowledge for evolution. *Research in Science Education, 53*(2), 213-229. https://doi.org/10.1007/s11165-022-10042-0

Behling, F., Förtsch, C., & Neuhaus, B. J. (2022). The refined consensus model of pedagogical content knowledge (PCK): Detecting filters between the realms of PCK. *Education Sciences, 12*(9), Article 592. https://doi.org/10.3390/educsci12090592

Belew, R. K. (2005). Scientific impact quantity and quality: Analysis of two sources of bibliographic data. *arXiv*. https://doi.org/10.48550/arXiv.cs/0504036

Berry, A., Depaepe, F., & van Driel, J. (2016). Pedagogical content knowledge in teacher education. In J. Loughran, & M. L. Hamilton (Eds.), *International handbook of teacher education* (pp. 347-386). Springer. https://doi.org/10.1007/978-981-10-0366-0_9

Berry, A., Friedrichsen, P. J., & Loughran, J. (Eds.). (2015). *Re-examining pedagogical content knowledge in science education* (vol. 395). Routledge. https://doi.org/10.4324/9781315735665

Bogdan, R. (2022). Elementary school students' interests and attitudes towards biology and physics. *Journal of Biological Education, 58*(4), 972-983. https://doi.org/10.1080/00219266.2022.2147208

Bravo, P., & Cofré, H. (2016). Developing biology teachers' pedagogical content knowledge through learning study: The case of teaching human evolution. *International Journal of Science Education, 38*(16), 2500-2527. https://doi.org/10.1080/09500693.2016.1249983

Bulick, S. (1978). Book use as a Bradford-Zipf phenomenon. *College & Research Libraries, 39*(3), 215-219. https://doi.org/10.5860/crl_39_03_215

Carlson, J., Stokes, L., Helms, J., Julie, G. N., & Gardner, A. (2015). The PCK summit: A process and structure for challenging current ideas, provoking future work, and considering new directions. In A. Berry, P. Friedrichsen, & J. Loughran (Eds.), *Re-examining pedagogical content knowledge in science education* (pp. 14-27). Routledge. https://doi.org/10.4324/9781315735665

Carlson, J., Daehler, K. R., Alonzo, A. C., Barendsen, E., Berry, A., Borowski, A., Carpendale, J., Chan, K. K. H., Cooper, R., Friedrichsen, P., Gess-Newsome, J., Henze-Rietveld, I., Hume, A., Kirschner, S., Liepertz, S., Loughran, J., Mavhunga, E., Neumann, K., Nilsson, P., ..., & Wilson, C. D. (2019). The refined consensus model of pedagogical content knowledge in science education. In A. Hume, R. Cooper, & A. Borowski (Eds.), *Repositioning pedagogical content knowledge in teachers' knowledge for teaching science* (pp. 77-94). Springer. https://doi.org/10.1007/978-981-13-5898-2_2

Chan, K. K. H., & Hume, A. (2019). Towards a consensus model: Literature review of how science teachers' pedagogical content knowledge is investigated in empirical studies. In A. Hume, R. Cooper, & A. Borowski (Eds.), *Repositioning pedagogical content knowledge in teachers' knowledge for teaching science* (pp. 3-76). Springer. https://doi.org/10.1007/978-981-13-5898-2_1

Chantaranima, T., & Yuenyong, C. (2018). Competencies of Thai expertise teacher and PCK. *AIP Conference Proceedings, 1923*(1), Article 030065. https://doi.org/10.1063/1.5019556

Coile, R. C. (1977). Lotka's frequency distribution of scientific productivity. *Journal of the American Society for Information Science, 28*(6), 366-370. https://doi.org/10.1002/asi.4630280610

Cooper, R., & van Driel, J. (2019). Developing research on PCK as a community. In A. Hume, R. Cooper, & A. Borowski (Eds.), *Repositioning pedagogical content knowledge in teachers' knowledge for teaching science* (pp. 303-315). Springer. https://doi.org/10.1007/978-981-13-5898-2_14

CPEIP. (2021). Marco para la buena enseñanza [Framework for good teaching]. *Ministerio de Educación, Chile*. https://estandaresdocentes.mineduc.cl/wp-content/uploads/2021/08/MBE-2.pdf

Cretu, D. M., & Morandau, F. (2020). Initial teacher education for inclusive education: A bibliometric analysis of educational research. *Sustainability,* *12*(12), Article 4923. https://doi.org/10.3390/su12124923

Depaepe, F., Verschaffel, L., & Kelchtermans, G. (2013). Pedagogical content knowledge: A systematic review of the way in which the concept has pervaded mathematics educational research. *Teaching and Teacher Education, 34*, 12-25. https://doi.org/10.1016/j.tate.2013.03.001

Doğru, M., Çelik, M., & Satar, C. (2019). Bibliometric profile of scientific studies on pedagogical content knowledge. *Socialinis Ugdymas/Social Education, 51*(1), 6-23. https://doi.org/10.15823/su.2019.51.1

Donthu, N., Kumar, S., Mukherjee, D., Pandey, N., & Lim, W. M. (2021). How to conduct a bibliometric analysis: An overview and guidelines. *Journal of Business Research, 133*, 285-296. https://doi.org/10.1016/j.jbusres.2021.04.070

Drăghicescu, L. M., Petrescu, A. M. A., Stăncescu, I., & Gorghiu, L. M. (2018). The relevance of continuous training programmes dedicated for teachers from pre-university education. *Revista Romaneasca pentru Educatie Multidimensionala, 10*(3), 6-16. https://doi.org/10.18662/rrem/58

Drake, S. M., & Reid, J. L. (2020). 21st century competencies in light of the history of integrated curriculum. *Frontiers in Education, 5*. https://doi.org/10.3389/feduc.2020.00122

Erduran, S., & Guilfoyle, L. (2022). The importance of research in science teacher education. In J. A. Luft, & M. G. Jones (Eds.), *Handbook of research on science teacher education* (pp. 5-15). Routledge. https://doi.org/10.4324/9781003098478-2

Ergönenç, J., Neumann, K., & Fischer, H. E. (2014). The impact of pedagogical content knowledge on cognitive activation and student learning. In H. E. Fischer, P. Labudde, K. Neumann, & J. Viiri (Eds.), *Quality of instruction in physics–Comparing Finland, Germany and Switzerland* (pp. 145-160). Waxmann. https://shorturl.at/5Cy5m

Escribano Hervis, E. (2018). El desempeño del docente como factor asociado a la calidad educativa en América Latina [Teacher performance as a factor associated with educational quality in Latin America]. *Revista Educación, 42*(2), 738-752. https://doi.org/10.15517/revedu.v42i2.27033

Gess-Newsome, J. (2015). A model of teacher professional knowledge and skill including PCK: Results of the thinking from the PCK Summit. In *Re-examining pedagogical content knowledge in science education* (pp. 28-42). Routledge.

Gess-Newsome, J., & Lederman, N. G. (Eds.). (1999). *Examining pedagogical content knowledge: The construct and its implications for science education* (vol. 6). Springer. https://doi.org/10.4324/9781315735665

Gess-Newsome, J., Taylor, J. A., Carlson, J., Gardner, A. L., Wilson, C. D., & Stuhlsatz, M. A. (2019). Teacher pedagogical content knowledge, practice, and student achievement. *International Journal of Science Education, 41*(7), 944-963. https://doi.org/10.1080/09500693.2016.1265158

Gil-Doménech, D., Berbegal-Mirabent, J., & Merigó, J. M. (2020). STEM education: A bibliometric overview. In *Proceedings of the International Conference on Modelling and Simulation in Management Sciences* (pp. 193-205). Springer. https://doi.org/10.1007/978-3-030-15413-4

González-Escobar, M., Silva-Peña, I., Gandarillas, A. P., & Kelchtermans, G. (2020). Abandono docente en América Latina: Revisión de la literatura [Teacher attrition in Latin America: Literature review]. *Cadernos de Pesquisa, 50*(176), 592-604. https://doi.org/10.1590/198053146706

Güner, P., & Gökçe, S. (2021). Monitoring the nomological network of number sense studies. *International Journal of Mathematical Education in Science and Technology, 52*(4), 580-608. https://doi.org/10.1080/0020739x.2021.1895343

Hagevik, R., Veal, W., Brownstein, E. M., Allan, E., Ezrailson, C., & Shane, J. (2010). Pedagogical content knowledge and the 2003 science teacher preparation standards for NCATE accreditation or state approval. *Journal of Science Teacher Education, 21*(1), 7-12. https://doi.org/10.1007/s10972-009-9155-6

Hallinger, P., & Kulophas, D. (2019). The evolving knowledge base on leadership and teacher professional learning: A bibliometric analysis of the literature, 1960-2018. *Professional Development in Education, 46*(4), 521-540. https://doi.org/10.4324/9781003357384-2

Henze, I., & van Driel, J. (2015). Toward a more comprehensive way to capture PCK in its complexity. In A. Berry, P. Friedrichsen, & J. Loughran (Eds.), *Re-examining pedagogical content knowledge in science education* (pp. 130-144). Routledge. https://doi.org/10.4324/9781315735665-15

Hill, H. C., & Ball, D. L. (2004). Learning mathematics for teaching: Results from California's mathematics professional development institutes. *Journal for Research in Mathematics Education, 35*(5), 330-351. https://doi.org/10.2307/30034819

Hill, H. C., Ball, D. L., & Schilling, S. G. (2008). Unpacking pedagogical content knowledge: Conceptualizing and measuring teachers' topic-specific knowledge of students. *Journal for Research in Mathematics Education, 39*(4), 372-400. https://doi.org/10.5951/jresematheduc.39.4.0372

Hirsch, J. E. (2005). An index to quantify an individual's scientific research output. *PNAS, 102*(46), 16569-16572. https://doi.org/10.1073/pnas.0507655102

Holmgren, M., & Schnitzer, S. A. (2004). Science on the rise in developing countries. *PLoS Biology, 2*(1), Article e1. https://doi.org/10.1371/journal.pbio.0020001

Hume, A., Cooper, R., & Borowski, A. (Eds.). (2019). *Repositioning pedagogical content knowledge in teachers' knowledge for teaching science*. Springer. https://doi.org/10.1007/978-981-13-5898-2

Infante-Malachias, M. E., & Araya-Crisóstomo, S. (2023). Interdisciplinariedad como desafío para educar en la contemporaneidad [Interdisciplinarity as a challenge for education in contemporary times]. *Educar em Revista, 39*, Article e88371. https://doi.org/10.1590/1984-0411.88371

Irwanto, I. (2021). Research trends in technological pedagogical content knowledge (TPACK): A systematic literature review from 2010 to 2021. *European Journal of Educational Research, 10*(4), 2045-2054. https://doi.org/10.12973/eu-jer.10.4.2045

Kadirhanoğulları, M. K., & Köse, E. Ö. (2024). A bibliometric analysis of articles on bibliometric studies in science education. *International Journal of Research in Education and Science, 10*(2), 315-339. https://doi.org/10.46328/ijres.3370

Kraft, M. A., & Lyon, M. A. (2024). *The rise and fall of the teaching profession: Prestige, interest, preparation, and satisfaction over the last half century*. National Bureau of Economic Research. https://doi.org/10.3386/w32386

Kunter, M., Klusmann, U., Baumert, J., Richter, D., Voss, T., & Hachfeld, A. (2013). Professional competence of teachers: Effects on instructional quality and student development. *Journal of Educational Psychology, 105*(3), 805-820. https://doi.org/10.1037/a0032583

Kurt-Birel, G., Deniz, Ş., & Önel, F. (2020). Analysis of primary school teachers' knowledge of geometry. *International Electronic Journal of Elementary Education, 12*(4), 303-309. https://doi.org/10.26822/iejee.2020459459

Larraín, A., Gómez, M., Calderón, M., Fortes, G., Ramírez, F., Guzmán, V., & Cofré, H. (2022). Descripción del conocimiento pedagógico del contenido de la argumentación en docentes que enseñan ciencias naturales en educación pública en Chile [Description of pedagogical content knowledge of argumentation in teachers who teach natural sciences in public education in Chile]. *Revista Eureka sobre Enseñanza y Divulgación de las Ciencias, 19*(1), 160201-160219. https://doi.org/10.25267/Rev_Eureka_ensen_divulg_cienc.2022.v19.i1.1602

Lavonen, J. (2018). Educating professional teachers in Finland through the continuous improvement of teacher education programmes. In Y. Weinberger, & Z. Libman (Eds.), *Contemporary pedagogies in teacher education and development*. InTech. https://doi.org/10.5772/intechopen.77979

Lee, E., Brown, M. N., Luft, J. A., & Roehrig, G. H. (2007). Assessing beginning secondary science teachers' PCK: Pilot year results. *School Science and Mathematics, 107*(2), 52-60. https://doi.org/10.1111/j.1949-8594.2007.tb17768.x

Li, S., Liu, L., & Jiang, A. L. (2021). Understanding the development of Chinese EFL student-teachers' pedagogical content knowledge. *Frontiers in Psychology, 12*. https://doi.org/10.3389/fpsyg.2021.627728

Loughran, J. (2016). Teaching and teacher education: The need to go beyond rhetoric. In R. Brandenburg, S. McDonough, J. Burke, & S. White (Eds.), *Teacher education* (pp. 253-264). Springer. https://doi.org/10.1007/978-981-10-0785-9_15

Luft, J. A., Navy, S. L., Wong, S. S., & Hill, K. M. (2022). The first 5 years of teaching science: The beliefs, knowledge, practices, and opportunities to learn of secondary science teachers. *Journal of Research in Science Teaching, 59*(9), 1692-1725. https://doi.org/10.1002/tea.21771

Magnusson, S., Krajcik, J., & Borko, H. (1999). Nature, sources, and development of pedagogical content knowledge for science teaching. In J. Gess-Newsome, & N. G. Lederman (Eds.), *Examining pedagogical content knowledge* (pp. 95-132). Kluwer Academic Publishers. https://doi.org/10.1007/0-306-47217-1_4

Mahler, D., Großschedl, J., & Harms, U. (2017). Using doubly latent multilevel analysis to elucidate relationships between science teachers' professional knowledge and students' performance. *International Journal of Science Education, 39*(2), 213-237. https://doi.org/10.1080/09500693.2016.1276641

Maral, M. (2024). A bibliometric analysis of global research on education in the Scopus Database, 2013-2022. *Global Knowledge, Memory and Communication*. https://doi.org/10.1108/GKMC-01-2024-0039

Masic, I., Jankovic, S., Donev, D., Zildzic, M., & Hozo, I. (2022). Operation of medical journal citation databases without control. Dilemma: Are they what they want to be in the eyes of scientific community. *Materia Socio-Medica, 34*(4), 248-253. https://doi.org/10.5455/msm.2022.34.248-253

McNeill, K. L., González-Howard, M., Katsh-Singer, R., & Loper, S. (2016). Pedagogical content knowledge of argumentation: Using classroom contexts to assess high-quality PCK rather than pseudoargumentation. *Journal of Research in Science Teaching, 53*(2), 261-290. https://doi.org/10.1002/tea.21252

Medina-Jerez, W. (2018). Science education research trends in Latin America. *International Journal of Science and Mathematics Education, 16*, 465-485. https://doi.org/10.1007/s10763-016-9785-z

Mientus, L., Hume, A., Wulff, P., Meiners, A., & Borowski, A. (2022). Modelling STEM teachers' pedagogical content knowledge in the framework of the refined consensus model: A systematic literature review. *Education Sciences, 12*(6), Article 385. https://doi.org/10.3390/educsci12060385

Mishra, P., & Koehler, M. J. (2006). Technological pedagogical content knowledge: A framework for teacher knowledge. *Teachers College Record, 108*(6), 1017-1054. https://doi.org/10.1111/j.1467-9620.2006.00684.x

Mombaers, T., Van Gasse, R., Vanlommel, K., & Van Petegem, P. (2023). 'To teach or not to teach?' An exploration of the career choices of educational professionals. *Teachers and Teaching, 29*(7-8), 788-820. https://doi.org/10.1080/13540602.2023.2201425

Mongeon, P., & Paul-Hus, A. (2016). The journal coverage of Web of Science and Scopus: A comparative analysis. *Scientometrics, 106*, 213-228. https://doi.org/10.1007/s11192-015-1765-5

Monte-Sano, C., & Budano, C. (2013). Developing and enacting pedagogical content knowledge for teaching history: An exploration of two novice teachers' growth over three years. *Journal of the Learning Sciences, 22*(2), 171-211. https://doi.org/10.1080/10508406.2012.742016

Morse, P. M., & Leimkuhler, F. F. (1979). Exact solution for the Bradford distribution and its use in modeling informational data. *Operations Research, 27*(1), 187-198. https://doi.org/10.1287/opre.27.1.187

Mukherjee, D., Lim, W. M., Kumar, S., & Donthu, N. (2022). Guidelines for advancing theory and practice through bibliometric research. *Journal of Business Research, 148*, 101-115. https://doi.org/10.1016/j.jbusres.2022.04.042

Nasir, Bancong, H., Sukmawati, & Hambali, U. (2023). Bibliometric analysis of TPACK publication trends in Scopus Database from 2013 to 2022. *Studies in Learning and Teaching, 4*(1), 109-122 https://doi.org/10.46627/silet

Nilsson, P., & Elm, A. (2017). Capturing and developing early childhood teachers' science pedagogical content knowledge through CoRes. *Journal of Science Teacher Education, 28*(5), 406-424. https://doi.org/10.1080/1046560X.2017.1347980

Nilsson, P., & Karlsson, G. (2019). Capturing student teachers' pedagogical content knowledge (PCK) using CoRes and digital technology. *International Journal of Science Education, 41*(4), 419-447. https://doi.org/10.1080/09500693.2018.1551642

Özkaya, A. (2018). Bibliometric analysis of the studies in the field of mathematics education. *Educational Research and Reviews, 13*(22), 723-734. https://doi.org/10.5897/ERR2018.3603

Park, S., & Chen, Y.-C. (2012). Mapping out the integration of the components of pedagogical content knowledge (PCK): Examples from high school biology classrooms. *Journal of Research in Science Teaching, 49*(7), 922-941. https://doi.org/10.1002/tea.21022

Park, S., & Suh, J. K. (2015). From portraying toward assessing PCK: Drivers, dilemmas, and directions for future research. In A. Berry, P. Friedrichsen, & J. Loughran (Eds.), *Re-examining pedagogical content knowledge in science education* (pp. 114-129). Routledge. https://doi.org/10.4324/9781315735665-14

Park, S., Choi, A., & Reynolds, W. M. (2020). Cross-national investigation of teachers' pedagogical content knowledge (PCK) in the US and South Korea: What proxy measures of teacher quality are related to PCK? *International Journal of Science Education, 42*(15), 2630-2651. https://doi.org/10.1080/09500693.2020.1823046

Perianes-Rodriguez, A., Waltman, L., & Van Eck, N. J. (2016). Constructing bibliometric networks: A comparison between full and fractional counting. *Journal of Informetrics, 10*(4), 1178-1195. https://doi.org/10.1016/j.joi.2016.10.006

Pranckutė, R. (2021). Web of Science (WoS) and Scopus: The titans of bibliographic information in today's academic world. *Publications, 9*(1), Article 12. https://doi.org/10.3390/publications9010012

Price, D. D. S. (1976). A general theory of bibliometric and other cumulative advantage processes. *Journal of the American Society for Information Science, 27*(5), 292-306. https://doi.org/10.1002/asi.4630270505

Ravanal Moreno, E., Ottogalli, E., López-Cortés, F., Alarcón Barraza, J. F., & Amórtegui Cedeño, E. (2024). Characterisation of the pedagogical knowledge of evolution content using the mapping approach. *Journal of Biological Education*. https://doi.org/10.1080/00219266.2024.2365659

Reimers, F. M. (2020). *Educating students to improve the world*. Springer. https://doi.org/10.1007/978-981-15-3887-2

Rollnick, M. (2017). Learning about semi-conductors for teaching–The role played by content knowledge in pedagogical content knowledge (PCK) development. *Research in Science Education, 47*(4), 833-868. https://doi.org/10.1007/s11165-016-9530-1

Sainaghi, R., Phillips, P., Baggio, R., & Mauri, A. (2018). Cross-citation and authorship analysis of hotel performance studies. *International Journal of Hospitality Management, 73*, 75-84. https://doi.org/10.1016/j.ijhm.2018.02.004

Santibáñez, D., Vergara, C., & Cofré, H. (2021). El desarrollo del CPC de profesores de biología en ejercicio [The development of PCK of practicing biology teachers]. In Cofré, H., Vergara, C., & Spotorno, A. (Eds.), *Enseñar evolución y genética para la alfabetización científica* (pp. 23-39). Ediciones Universitarias de Valparaíso de la Pontificia Universidad Católica de Valparaíso. https://doi.org/10.2307/j.ctv2br107w

Sarkar, M., Gutierrez-Bucheli, L., Yip, S. Y., Lazarus, M., Wright, C., White, P. J., Ilic, D., Hiscox, T. J., & Berry, A. (2024). Pedagogical content knowledge (PCK) in higher education: A systematic scoping review. *Teaching and Teacher Education, 144*, Article 104608. https://doi.org/10.1016/j.tate.2024.104608

Schmelzing, S., van Driel, J. H., Jüttner, M., Brandenbusch, S., Sandmann, A., & Neuhaus, B. J. (2013). Development, evaluation, and validation of a paper-and-pencil test for measuring two components of biology teachers' pedagogical content knowledge concerning the "cardiovascular system". *International Journal of Science and Mathematics Education, 11*(6), 1369-1390. https://doi.org/10.1007/s10763-012-9384-6

Schneider, R. M., & Plasman, K. (2011). Science teacher learning progressions: A review of science teachers' pedagogical content knowledge development. *Review of Educational Research, 81*(4), 530-565. https://doi.org/10.3102/0034654311423382

Shiffrin, R. M., & Börner, K. (2004). Mapping knowledge domains. *PNAS, 101*(suppl_1), 5183-5185. https://doi.org/10.1073/pnas.0307852100

Shulman, L. (1987). Knowledge and teaching: Foundations of the new reform. *Harvard Educational Review, 57*(1), 1-23. https://doi.org/10.17763/haer.57.1.j463w79r56455411

Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. *Educational Researcher, 15*(2), Article 4. https://doi.org/10.2307/1175860

Shulman, L. S. (2015). PCK: Its genesis and exodus. In A. Berry, P. Friedrichsen, & J. Loughran (Eds.), *Re-examining pedagogical content knowledge in science education* (pp. 3-13). Routledge. https://doi.org/10.4324/9781315735665-6

Sleeter, C. (2014). Toward teacher education research that informs policy. *Educational Researcher, 43*(3), 146-153. https://doi.org/10.3102/0013189X14528752

Smit, E., Tuithof, H., Savelsbergh, E., & Béneker, T. (2023). Geography teachers' pedagogical content knowledge: A systematic review. *Journal of Geography, 122*(1), 20-29. https://doi.org/10.1080/00221341.2023.2173796

Song, Y., Chen, X., Hao, T., Liu, Z., & Lan, Z. (2019). Exploring two decades of research on classroom dialogue by using bibliometric analysis. *Computers & Education, 137*, 12-31. https://doi.org/10.1016/j.compedu.2019.04.002

Tuithof, H., Logtenberg, A., van Drie, J., Bronkhorst, L. H., & van Tartwijk, J. W. F. (2019). What do we know about the pedagogical content knowledge of history teachers?: A review of empirical research. *Historical Encounters, 2019*(6), 72-95. https://shorturl.at/BvAZv.

Tuithof, H., Van Drie, J., Bronkhorst, L., Dorsman, L., & Van Tartwijk, J. (2023). Teachers' pedagogical content knowledge of two specific historical contexts captured and compared. *Educational Studies, 49*(4), 686-711. https://doi.org/10.1080/03055698.2021.1877621

Valero-Matas, J. A., & Coca J., P. (2021). La percepción de las materias STEM en estudiantes de primaria y secundaria [The perception of STEM subjects in primary and secondary school students]. *Sociología y Tecnociencia: Revista Digital de Sociología del Sistema Tecnocientífico, 11*(1), 116-138. https://doi.org/10.24197/st.Extra_1.2021.116-138

van der Jagt, E., & Nielsen, W. (2024). Preservice primary teacher pedagogical content knowledge of fractions using the refined consensus model. In J. Višňovská, E. Ross, & S. Getenet (Eds.), *Proceedings of the 46th Annual Conference of the Mathematics Education Research Group of Australasia* (pp. 543-550). MERGA.

van Driel, J. H., & Berry, A. (2012). Teacher professional development focusing on pedagogical content knowledge. *Educational Researcher, 41*(1), 26-28. https://doi.org/10.3102/0013189x11431010

van Driel, J. H., Hume, A., & Berry, A. (2023). Research on science teacher knowledge and its development. In N. G. Lederman, D. L. Zeidler, & J. S. Lederman (Eds.), *Handbook of research on science education* (pp. 1123-1161). Routledge. https://doi.org/10.4324/9780367855758-41

Vergara, C., Bassaber, A., Núñez Nieto, P., Becerra, B., Hurtado, H., Santibáñez, D., & Cofré, H. (2024). A map of collective pedagogical content knowledge as a basis for studying the development of biology teachers' personal PCK of evolution. *International Journal of Science Education*. https://doi.org/10.1080/09500693.2024.2381841

Vergara, C., Cofré, H., & Santibáñez, D. (2021). Enseñanza de biología y conocimiento pedagógico del contenido: Una introducción [Biology teaching and pedagogical content knowledge: An introduction]. In H. Cofré, C. Vergara, & A. Spotorno (Eds.), *Enseñar evolución y genética para la alfabetización científica*. Ediciones Universitarias de Valparaíso de la Pontificia Universidad Católica de Valparaíso. https://doi.org/10.2307/j.ctv2br107w.6

Waltman, L., Van Eck, N. J., & Noyons, E. C. (2010). A unified approach to mapping and clustering of bibliometric networks. *Journal of Informetrics, 4*(4), 629-635. https://doi.org/10.1016/j.joi.2010.07.002

Wang, S., Chen, Y., Lv, X., & Xu, J. (2023). Hot topics and frontier evolution of science education research: A bibliometric mapping from 2001 to 2020. *Science & Education, 32*(3), 845-869. https://doi.org/10.1007/s11191-022-00337-z

Ward, P., & Ayvazo, S. (2016). Pedagogical content knowledge: Conceptions and findings in physical education. *Journal of Teaching in Physical Education, 35*(3), 194-207. https://doi.org/10.1123/jtpe.2016-0037

Wilson, C. D., Borowski, A., & van Driel, J. (2019). Perspectives on the future of PCK research in science education and beyond. In A. Hume, R. Cooper, & A. Borowski (Eds.), *Repositioning pedagogical content knowledge in teachers' knowledge for teaching science* (pp. 291-302). Springer. https://doi.org/10.1007/978-981-13-5898-2_13

Yang, Y., Liu, X., & Gardella, J. A. (2018). Effects of professional development on teacher pedagogical content knowledge, inquiry teaching practices, and student understanding of interdisciplinary science. *Journal of Science Teacher Education, 29*(4), 263-282. https://doi.org/10.1080/1046560X.2018.1439262

Ye, J., Chen, D., & Kong, L. (2019). Bibliometric analysis of the WoS literature on research of science teacher from 2000 to 2017. *Journal of Baltic Science Education, 18*(5), 732-747. https://doi.org/10.33225/jbse/19.18.732

Yig, K. G. (2022). Research trends in mathematics education: A quantitative content analysis of major journals 2017-2021. *Journal of Pedagogical Research, 6*(3), 137-153. https://doi.org/10.33902/jpr.202215529

Zhang, M., Parker, J., Koehler, M. J., & Eberhardt, J. (2015). Understanding inservice science teachers' needs for professional development. *Journal of Science Teacher Education, 26*(5), 471-496. https://doi.org/10.1007/s10972-015-9433-4

Zipf, G. K. (1932). *Selected studies of the principle of relative frequency in language*. Harvard University Press. https://doi.org/10.4159/harvard.9780674434929

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