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Review

Physics pedagogical content knowledge in the 21st century: A bibliometric analysis using Web of Science and CiteSpace

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Abstract

Pedagogical content knowledge is central to teacher knowledge and a focal point of research in teacher education. In particular, pedagogical content knowledge in physics has emerged as a significant area in the international science education research community, attracting considerable scholarly attention in the 21st century. This study analysed, synthesized, and visualized the hot topics as well as frontier evolution of physics pedagogical content knowledge using CiteSpace and VOSviewer visualisation software and literature indexed in the Web of Science Core Collection between 2000 and 2023. Journal analysis, temporal distribution analysis, citation trends analysis, core authors analysis, co-occurrence analysis and cluster analysis were conducted based on 132 articles retrieved from Web of Science. The literature on physics PCK mainly covered seven hot topics: pre-service physics teachers, pedagogical content knowledge, science education, understanding energy, knowledge acquisition, classroom practice and coping strategies. The research on physics PCK can be divided into 5 phases: slow development period, slow progress period, disturbance period, burst period and steady-state period. The study can enhance the quality of research and education in physics pedagogical content knowledge.

Keywords: physics, pedagogical content knowledge (PCK), Citespace, bibliometric analysis

1. Introduction

In recent years, the knowledge base of science teachers has become a research hotspot in the field of education (Kulaksiz & Karaca, 2023; Mikeska et al., 2023; Sen, 2023). Most of this research is grounded in the theoretical framework proposed by Shulman(Shulman, 1987; Shulman, 1986), who categorised teachers' professional knowledge into seven domains: knowledge of the content to be taught; general pedagogical knowledge; knowledge of the curriculum; pedagogical content knowledge (PCK); knowledge of learners and their characteristics; knowledge of educational contexts; and knowledge of the aims, purposes, values, and historical and philosophical foundation of education. PCK represents the core of teacher knowledge, integrating knowledge about learners, curriculum, teaching contexts, and pedagogical strategies. PCK is an acknowledgement to the importance of the transformation of subject matter knowledge per se into subject matter knowledge for teaching (Park & Oliver, 2008).

PCK remains a critical topic in educational research and focus for teachers' professional development. Many of these publications on PCK are written in the field of natural sciences, mostly in physics, chemistry and mathematics (Buma et al., 2023; Harrell et al., 2022; Vollmer & Klette, 2023). Various scholars have explored the essence and structure of PCK, suggesting that it fundamentally integrates subject and pedagogical knowledge to address specific topics or problems tailored to the interests and capabilities of diverse learners. Grossman (Grossman, 1990) conceptualized PCK as consisting of four components: (a) general pedagogical knowledge, (b) subject matter knowledge, (c) pedagogical content knowledge, (d) knowledge of context. Of the four knowledge components, PCK is considered to have the greatest impact on teachers' classroom behavior. Magnusson (Magnusson et al., 1999) conceptualized PCK for science teaching as consisting of five components: (a) orientations toward science teacling, (b) knowledge and beliefs about science curriculum, (c) knowledge and beliefs about students' understanding of specific science topics, (d) knowledge and beliefs about assessment in science, and (e) knowledge and beliefs about instructional strategies for teaching science. This model has formed the theoretical basis for much research on science PCK (Beyer & Davis, 2012). Koehler and Mishra (2005) (Koehler & Mishra, 2005) proposed technological pedagogical content knowledge (TPCK or TPACK) as an integrated description for technology knowledge, pedagogy knowledge, and content knowledge. Its conceptual interplays gave rise to seven independent constructs, namely, (a) technological knowledge, (b) pedagogical knowledge, (c) content knowledge, (d) technological content knowledge, (e) technological pedagogical knowledge, (f) pedagogical content knowledge, and (g) technological pedagogical content knowledge. TPACK is now commonly used as a theoretical framework to address the challenges of teaching in the digital age (Chuang et al., 2015).

Eugenia Etkina (Etkina, 2010) pointed out that physics teachers' PCK includes five elements : Orientation to science teaching; Knowledge of curricula; Knowledge of students' prior understandings about and difficulties with key concepts and practices in science; Knowledge of instructional strategies to scaffold students' learning of key concepts and practices in science. Ball (Loewenberg Ball et al., 2008) described mathematics PCK as a blending of knowledge of students' understanding of the content, knowledge of strategies for teaching the content, and knowledge of mathematics curriculum. Eulsun Seung et al. (Seung et al., 2012) identified a consensus of five components of PCK for science teaching. This PCK framework includes orientation towards science teaching, knowledge of student learning, knowledge of science curriculum, knowledge of instructional strategies for teaching science, knowledge of assessment in science. Chan (Chan & Hume, 2019) in their systematic review of how science teachers' pedagogical content knowledge is investigated in empirical studies, reported that science teachers' PCK include five components: knowledge of assessment, knowledge of curriculum, knowledge of instructional strategies and representations, knowledge of students' understanding, orientations to teaching science.

Teachers are not merely passive recipients of PCK; rather, they are expected to actively construct PCK through their experiences (Park & Oliver, 2008). Physics PCK involves the proactive integration of physics teachers' physics knowledge, pedagogical knowledge, and knowledge regarding students to facilitate students' understanding of physics concepts and their scientific nature.

However, the current research on physics PCK also faces many challenges, such as the insufficient support and participation of physics teachers, and psychological factors that may challenge or threaten students' learning achievement in phyiscs. Physics PCK epistemology is in short supply and its deficiency poses a threat to physics education. In the face of these challenges, clearer research maps and guidelines are needed to help physics PCK research more effectively.

This study examined the research frontiers, dynamics, and trends in the field of international physics education in the 21st century. The study used CiteSpace and VOSviewer to conduct a bibliometric analysis of the literature on physics PCK indexed in the Web of Science Core Collection.

2. Aims and Objectives

The current study aimed to systematically review the achievements of physics PCK research in the international science education community, and hope to provide an overall picture of the status and development of research on physics PCK, based on publication and citation data extracted from the Web of Science Core Collection from 2000 to 2023, and provide effective suggestions for physics teacher education.

The objectives were:

To synthesize the literature on physics PCK published in the Web of Science database ;

To summarize the research hotspots and research history of physics PCK, and provide suggestions for physics PCK research.

3. Research Methodology

3.1 General Background

Bradford's law describes the scatter of citations for a given subject or field. It can be used to identify the most highly cited journals for a field or subject. According to Bradford's law in library and information science, the latest achievements and core papers in a specific field are often concentrated in high-impact journals of that field (Venable et al., 2016).

Web of Science is an information retrieval platform that provides comprehensive indexing through its Core Collection. This study retrieved data from the Web of Science Core Collection to examine the progress and trends in research on physics PCK in the 21st century. The search was conducted on January 31, 2024, and explored the topics of "pedagogical content knowledge of physics" or "physics pedagogical content knowledge" or "physics PCK" or "PCK of physics." This study included articles from January 1, 2000, to January 31, 2024.

3.2 Data Analysis

The study was conducted in the form of bibliometric analysis, with data gathered via Web of Science Core Collection. This study employed the data analysis features inherent to the Web of Science system to obtain initial data charts. Subsequently, a visualisation analysis was conducted using CiteSpace 6.3 software (Chen, 2006, 2017) and VOSviewer 1.6.19 to generate relevant knowledge graphs. On the basis of these visualisations and further interpretation of related articles, we performed an analysis of the progress and trends in physics PCK research within the international science education field since the 21st century.

To visualise research using CiteSpace 6.3, the following steps were followed: (1) the retrieved Web of Science data were exported in text format and imported into CiteSpace for analysis; (2) the time span was set from 2000 to 2023, with a one-year interval for each time slice; (3) For "Term sources", "Ttitle""Abstract""Author keywords (DE)""Kewwords Plus(1D)" have been selected by default. For "Node type", "Institution" "Country" and "Keyword" were selected for analysis, the results were presented in the form of static clustering (Cluster View-static), and the merged network was displayed to visualise clustering graphs.

D. Price (Price, 1963) pointed out: In the same topic, half of the papers are written by a group of high-productivity authors, and the number of this collection of authors is about equal to the square root of the total number of all authors. This conclusion is called Price's Law. According to Price's Law, the formula to calculate the number of publications by core authors is $m_p = 0.749\sqrt{n_{pmax}}$, where mp is the minimum number of publications by a core author in a statistical period, and n_{pmax} is the number of publications by the most prolific author during the same period (Wang et al., 2022). In this study, we use this method to analyze the core authors of physics PCK research.

4. Research Results

4.1 Journal publication

The retrieved articles were published across 49 journals, as shown in Table 1. The *International Journal of Science Education* had the highest number of physics PCK articles, totalling 21. The *Physical Review Physics Education Research* (formerly known as *Physical Review Special Topics-Physics Education Research*), published 14 articles on the topic. The *Journal of Research in Science Teaching* published 12 articles, and the *Research in Science Education* published 10 articles. Among journals dedicated to physics, the *American Journal of Physics* published two articles, and the *European Journal of Physics* published one. The findings indicated that physics PCK research was predominantly published in science education journals, although physics-specific journals also had some articles on physics education.

Table 1. Journals Articles on Physics PCK

Journal Name	**Number of Publications**
International Journal of Science Education	21
Journal of Research in Science Teaching	12
Physical Review Physics Education Research	10

Research in Science Education	10
Journal of Baltic Science Education	7
Science Education	6
Computers & Education	4
Physical Review Special Topics-Physics Education Research	4
British Journal of Educational Technology	3
EURASIA Journal of Mathematics, Science & Technology Education	3
Chemistry Education Research and Practice	3
International Journal of STEM Education	3
Teaching and Teacher Education	3
Zeitschrift fur Erziehungswissenschaft	3
American Journal Of Physics	2
International Journal Of Science And Mathematics Education	2
Journal Of Science Education And Technology	2
Revista Brasileira De Ensino De Fisica	2
Studies In Higher Education	2
Applied Measurement In Education	1
Asia Pacific Education Researcher	1
Astrobiology	1
Australasian Journal Of Educational Technology	1
Education And Information Technologies	1
Educational Sciences Theory Practice	1
Engineering Computations	1
Ensenanza De Las Ciencias	1
Etr D Educational Technology Research And Development	1
European Journal Of Physics	1
European Journal Of Teacher Education	1
Heliyon	1
Higher Education	1
Journal Of Aerospace Information Systems	1
Journal Of Curriculum Studies	1
Journal Of Educational Psychology	1
Journal Of Professional Capital And Community	1
Journal Of Teacher Education	1
Linguistics And Education	1

Research In Science Technological Education	1
Revista Espanola De Pedagogia	1
Ried Revista Iberoamericana De Educacion A Distancia	1
Scandinavian Journal Of Educational Research	1
South African Journal Of Chemistry Suid Afrikaanse Tydskrif Vir Chemie	1
Studies In Educational Evaluation	1
Studies In Science Education	1
Teachers College Record	1
Teaching In Higher Education	1
Thinking Skills And Creativity	1
Zeitschrift Fur Padagogik	1

4.2 Temporal distribution and Citation trends

The search identified 132 valid articles on the topic of physics PCK, including 123 articles in English, four in German, three in Spanish, and two in Portuguese. These articles were published between September 2000 and October 2023. Of the retrieved articles, 126 were indexed in the Social Sciences Citation Index, 41 in the Science Citation Index Expanded, and five in the Arts & Humanities Citation Index. The retrieved articles received 2,396 citations, with a net citation count of 2,256 after excluding self-citations, averaging 18.15 citations per article. Figure 1 displays the annual publication volume and citation count trends over time. As illustrated in Figure 1, from 2016 onwards, the publication volume remained at a relatively stable level, indicating sustained scholarly interest and research in this area.

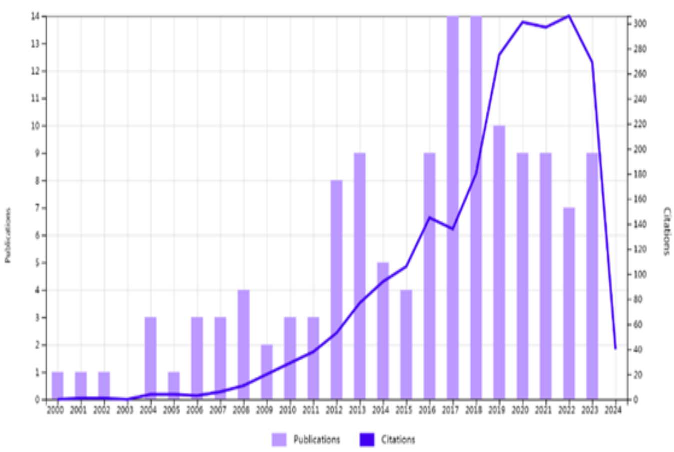

Figure 1. Annual publication volume and total citation counts for articles related to physics PCK

Nilsson (Nilsson, 2008) received the highest citation count of 164, with an average annual citation rate of 9.65. The study investigated the development of PCK among pre-service teachers in a 12-month programme, in which four pre-service teachers specialising in mathematics and science taught weekly physics lessons to students aged 9–11 years. The study focused on how these pre-service teachers identified and understood the subject knowledge, pedagogical knowledge, and knowledge of contexts that form the foundation of PCK.

Treagust and Harrison (Treagust & Harrison, 2000) received 44 citations, with an annual average of 1.76 citations. This article examined classifications of explanations in science teaching, including scientific, effective pedagogical, ordinary explanations, and elaborated on the concept of PCK, using the Lecture 1, entitled '*Atoms in motion*', from Richard Feynman's *Six Easy Pieces* as an example.

4.3 Author trends

The search results indicated that, between 2000 and 2023, the author with the most publications on physics PCK was Knut Neumann from the Leibniz Institute for Science and Mathematics Education, University of Kiel, with nine publications ($n_{pmax} = 9$). Therefore, $m_p = 2.247$. After rounding, authors with three or more publications were considered core contributors to physics PCK research. Eighteen core authors were identified (Table 2). As Table 2 shows, these authors appear as the prolific authors, and this result means that they have made distinctive contributions to the research on physics PCK. Scholars such as Knut Neumann, Josef Riese, Alicia C. Alonzo, Hans E. Fischer, Melanie M. Keller, Vicente Mellado are the most cited researchers, indicating that their studies have formed an essential knowledge base for following research. Moreover, universities were the primary institutions involved in physics PCK research. Leibniz Institute for Science and Mathematics Education, University of Kiel, was the institution with the highest number of publications in the field.

Table 2. Core Authors in Physics PCK Research

Author	Affiliation	Articles	Citations
Knut Neumann	Leibniz Institute for Science and Mathematics Education, University of Kiel	9	160
Stefan Sorge	Leibniz Institute for Science and Mathematics Education, University of Kiel	7	47
Josef Riese	RWTH Aachen University	7	108
Andreas Borowski	University of Potsdam	6	73
Christoph Kulgemeyer	University of Bremen	5	79
Peter Reinhold	University of Paderborn	5	60
Horst Schecker	University of Bremen	4	31
Alicia C. Alonzo	Michigan State University	4	144
Syh-Jong Jang	Asia University	4	60
Dustin Schiering	Leibniz Institute for Science and Mathematics Education, University of Kiel	4	3
Vicente Mellado	University of Extremadura	4	105
Florentina Cañada	University of Extremadura	3	34
Hans E. Fischer	University of Duisburg Essen	3	133
Jan Schröder	RWTH Aachen University	3	18
Christoph Vogelsang	University of Paderborn	3	18
Melanie M. Keller	Leibniz Institute for Science and Mathematics Education, University of Kiel	3	108
Alexandru Maries	University of Cincinnati	3	61
Chandralekha Singh	University of Pittsburgh	3	61

We used co-authorship analysis to identify leading authors and their cooperation networks by VOSviewer, as shown in figures 2 and 3. Figure 2 shows the collaboration network between authors in the dataset. In this graph, node size is positively related to the author's citation, and links exist if there were collaborations between authors. Figure 3 presents the knowledge graph of the collaboration network among these core authors. It can be seen from figure 3 that some core authors had close collaborations so as to form some academic groups or research groups. It is also worth noting that there are also subtle connections between different groups. This result shows that academic circle had formed between the core authors. Collaborations within and between these research teams facilitated the advancement of research in physics PCK.

Figure 4, generated by CiteSpace, 4 shows the scientific network between institutions with more than 2 publication. As shown in Figure 4, close cooperation of major research institutions had formed. It can be seen that the cooperative groups of the major research institutions were distributed in Germany and the United States.

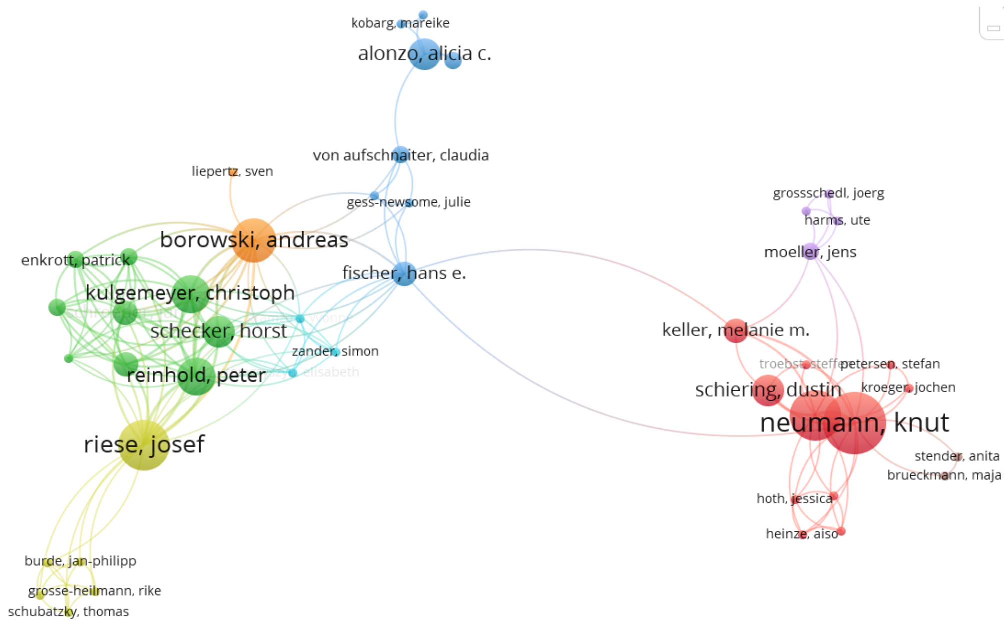

Figure 2. Collaborative research networks among authors

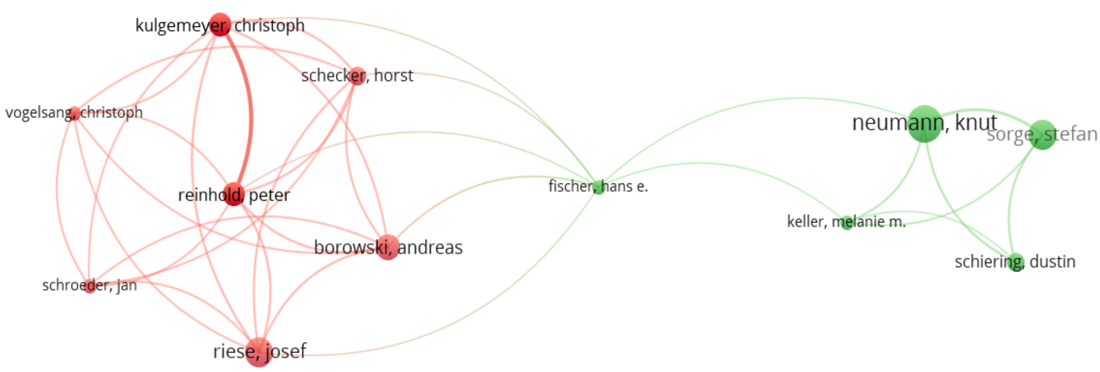

Figure 3. Collaboration network of physics PCK Core Authors

Figure 4. Collaborative research networks among institutions. Only institutions with 2 or more publications were considered in this map.

The distribution of publications by authors' country or region was as follows: the United States (37 articles), Germany (27 articles), South Africa (10 articles), mainland China and Hong Kong (8 articles), Taiwan (8 articles), Spain (7 articles), and Sweden (4 articles). Figure 5 shows the cooperative network diagram of the countries or territories studied. The results show that the Germany was at the center of physics PCK research, and it maintained links with Southe Africa, Netherlands, Poland, Switzerland, USA, Norway and Italy. Some countries or territories were far away from other countries or territories or have few links with others, indicating weak connections with other countries/territories.

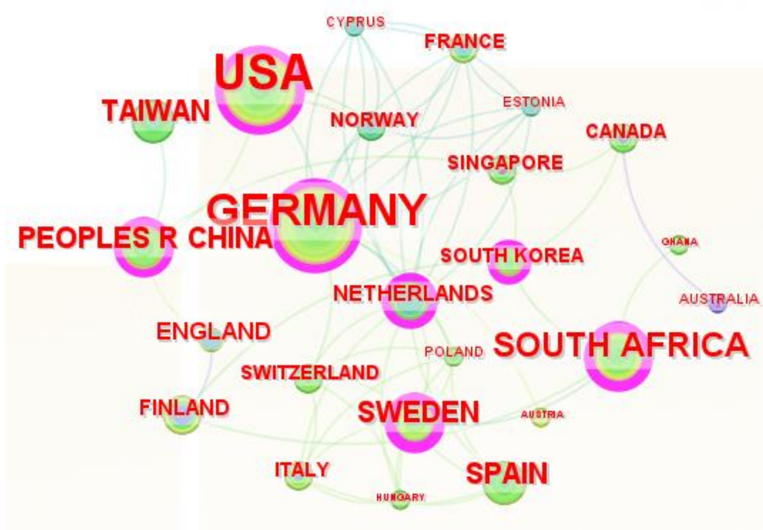

Figure 5. Collaborative research networks between countries and territories.

4.4 Keyword co-occurrence and clustering

To gain a deeper understanding of the research hotspots, an analysis of keywords was performed using the "Keyword" option in CiteSpace 6.3. The results revealed keyword co-occurrences. Keywords with frequencies of 8 or more are presented in Table 3, and a keyword co-occurrence graph is presented in Figure 6. The keyword co-occurrence graph comprised 298 nodes and 1,457 links. "Pedagogical content knowledge" appeared most frequently, with a betweenness centrality of 0.28. The keywords "science," "education", "physics" "science education" and "teacher education" also appeared frequently, with a betweenness centrality > 0.1. This indicated that these four keywords played crucial roles in physics PCK research.

Table 3. Keyword Co-occurrence Statistics (frequency ≥ 8)

Keyword	Frequency	Betweenness Centrality
Pedagogical content knowledge	71	0.28
Science	35	0.25
Education	28	0.22
Physics	23	0.14
Teachers	15	0.06
Beliefs	14	0.14
Science education	12	0.14
Students	11	0.04
Conceptions	10	0.09
PCK	10	0.03
Impact	9	0.09
Content knowledge	9	0.06
Achievement	8	0.11
Teacher education	8	0.14
Biology	8	0.05

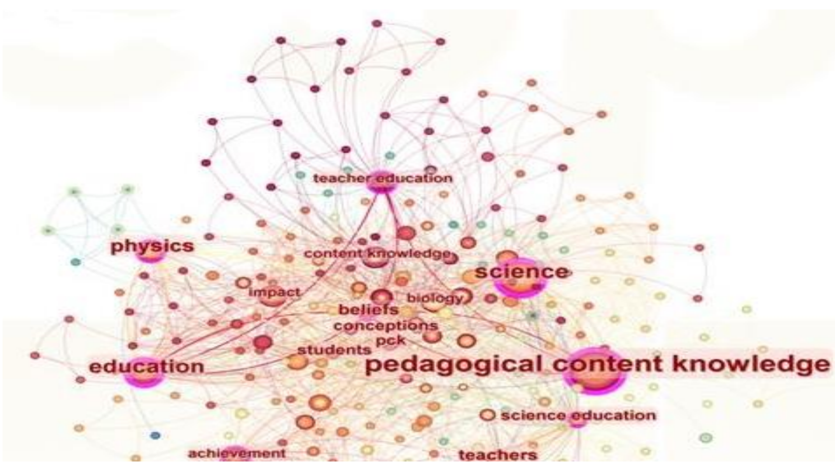

Figure 6. Keyword co-occurrence graph for physics PCK research

CiteSpace evaluates the clarity of network structure and clustering based on the modularity (Q) value and average silhouette (S) value. A Q value > 0.3 indicates a significant clustering structure, whereas an S value > 0.7 indicates efficient and convincing clustering (Chen et al., 2010; Chen et al., 2015). In Figure 6, the keyword co-occurrence graph revealed that Q was 0.6332 (> 0.3) and S was 0.8384 (> 0.7). This indicated that the keyword clustering graph was rational and credible.

CiteSpace was used to construct a timeline graph of the relationships between clusters and historical span of the literature in each cluster (Chen et al., 2010). Using CiteSpace software and selecting "cluster", the graph was obtained with 298 network nodes and 1457 connections, as shown in Figure 7. The network density was 0.0329. The value of Modularity Q was 0.5086, greater than the critical value 0.3, indicating that the significant community structure of the co-word network and good clustering effect. The mean silhouette value of 0.8384 is greater than the critical value of 0.7, indicating that the clustering results are reasonable. By using log likelihood ratio (LSI) algorithm, a total of 7 keyword clusters have been formed.

Hot topics help to explore the core knowledge nodes of physics PCK research. Figure 7 shows the timeline of the change of hot topics in physics PCK research. Each cluster is plotted horizontally. Each timeline runs from left to right with its label displayed to the right. Table 4 illustrates clusters of hot topics and time spans in physics PCK. The keyword clusters included #0 pre-service physics teachers, #1 pedagogical content knowledge, #2 science education, #3 understanding energy, #4 knowledge acquisition, #5 classroom practice, and #6 coping strategies. The cluster #0 pre-service physics teachers was the largest, with a silhouette value of 0.86, demonstrating a significant and sustained focus on the PCK of pre-service physics teachers.

As the number of clusters increases, the size becomes smaller. The silhouette score indicates the homogeneity or consistency of each cluster. When the members in the cluster tend to be homogeneous, the silhouette value is closer to 1 (Wang et al., 2022). These clusters clearly presented the core issues in international physics PCK research in the 21st century. In this study, cluster analysis was performed based on the indicators with larger weight in each cluster and articles involving these terms. The results show that the hot topics of physics PCK research mainly included pre-service physics teacher, pedagogical content knowledge, knowledge acquisition, science educaiton, understanding energy, knowledge acquisition, classroom practice, and coping strategies.

The duration of each cluster varied, indicating different research periods for each theme. Cluster #5, "classroom practice," had the longest duration, highlighting the emphasis that researchers place on classroom practices. Cluster #4, "knowledge acquisition," had the shortest span and ceased to be a hotspot after 2019. Clusters #0 ("pre-service physics teachers"), #5 ("classroom practice"), and #6 ("coping strategies") indicated continued research activity through to 2023, suggesting that these areas remained at the forefront and were hotspots in physics PCK research.

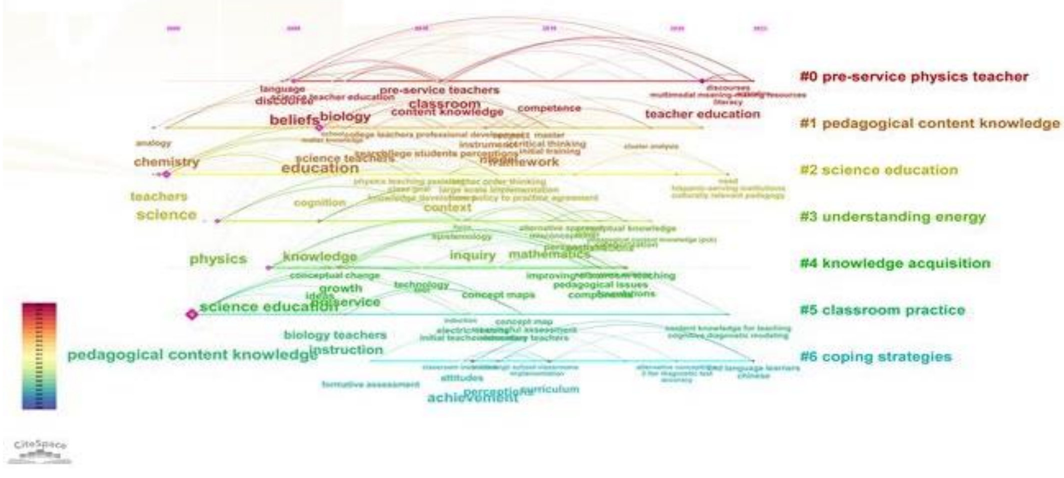

Figure 7. Timeline Graph of Keyword Clusters and Hotspots in Physics PCK Research

Table 4. Clusters of time Span and hot topics in physics PCK

Cluster	Nodes	Silhouette	Mean year	Time Span	Keywords (with LSI algorithm)
0	39	0.86	2016	2005–2023	pre-service physics teacher; content knowledge; pre-service science teacher; academic characteristics; basic chemical idea
1	32	0.814	2013	2000–2021	pedagogical content knowledge; case teacher; delphi survey technique; validating technological pedagogical content; case study
2	31	0.827	2011	2000–2022	pedagogical content knowledge; science education; whole school system; novel physics curriculum; pedagogical content knowledge development
3	31	0.848	2014	2002–2019	understanding energy; conceptual resource; university student; using scenario; complex technology-enhanced learning environment
4	25	0.820	2012	2004–2018	knowledge acquisition; game-based learning; game design creativity; customizing scaffold; early-years teacher
5	25	0.868	2012	2000–2023	classroom practice; scientific inquiry; teaching physics; beginning teacher; teaching children
6	24	0.837	2017	2001–2023	coping strategies; critical review; science classroom

4.5 Keyword burst

CiteSpace was used to identify burst terms and provide a comprehensive view of research hotspots and their evolution. The top 20 keywords in terms of burst strength were obtained through burst keywords detection, as shown in Figure 8, where "Year" is the year of the original publication, "Strength" is the emergent strength, "Begin" and "End" are the start and end times of the burst keywords, and the red line is the active time period of burst keywords, which means that the burst keywords have attracted a lot of attention from researchers during this time period. The burst analysis of keywords can help to reveal the trend of hot topics in related research fields, and the higher emergence intensity, the higher attention of the academic community (Li & Li, 2024).

The top five burst keywords by strength of burst were teacher education (3.91), teachers (3.03), PCK (2.81), professional development (2.33), and professional knowledge (2.14). "Teacher education" became a hotspot in 2021 and continued through 2023, although it had a short research period. "Teachers" appeared in 2000, burst in 2016, and had the longest research duration. The "PCK" abbreviation emerged in 2016 and has been a hotspot since 2019. "Professional development" appeared in 2011 and was a hotspot from 2020 to 2023. The keyword "students," with a burst strength of 1.59, appeared in 2001 and was a hotspot from 2018 to 2020, continuing its relevance through 2023. This indicated a significant focus on teacher professional development and student-related themes in the international physics PCK research community.

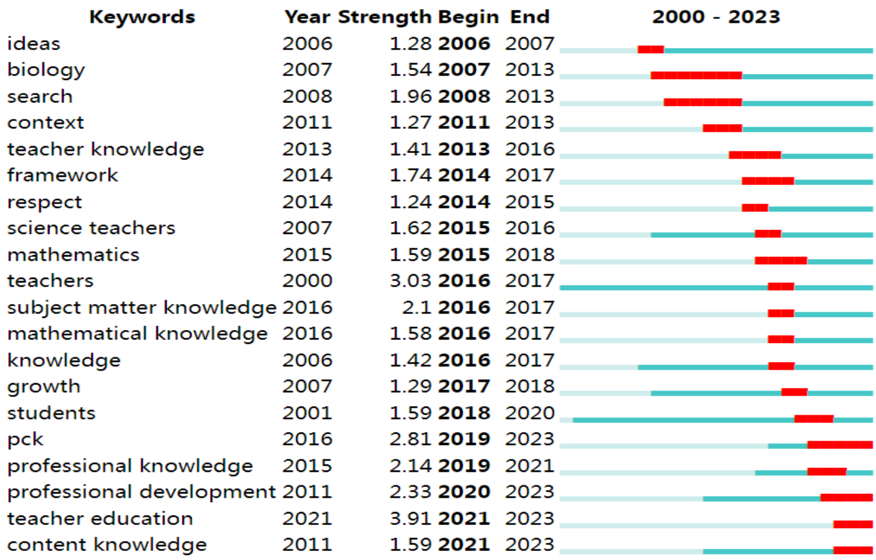

Figure 8. Keyword burst graph for physics PCK Research. Red lines indicate the duration when a keyword was a research hotspot, light blue represents nodes before their appearance, and dark blue marks the onset of their emergence.

4.6 Evolution of pysics PCK research

According to the appearances and meanings of high-frequency keywords and burst terms in each year, the research period of physics PCK can be roughly divided into 5 stages.

Stage one was the slow development period (2000–2005). During this stage, no keyword hotspots emerged, indicating a limited number of scholars engaged in physics PCK research and the narrow scope of published literature (7 papers, total times cited 143). By the way, it is unclear how the hotspots were indicated and assigned a specific period. Key research included the classification of scientific explanations in science teaching (Treagust & Harrison, 2000) , core concepts in physics teaching (Deng, 2001), professional development training for in-service physics teachers (Lavonen et al., 2004; Prather & Slater, 2002), teaching for understanding (Geelan et al., 2004), and strategies for teaching physics concepts (Grayson, 2004).

Stage two was the slow progress period (2006–2011). This stage saw the publication of 18 articles (total times cited 653), with research hotspots expanding to include teacher knowledge, science teachers, and subject knowledge. Notable studies included case studies on the development of pre-service teachers' physics PCK (Nilsson, 2008; Sperandeo-Mineo et al., 2006); the use of analogies to improve the teaching performance of pre-service teachers (James & Scharmann, 2007); a comparative study on the attitudes, subject knowledge, and PCK needs of primary student teachers in physics activities (Johnston & Ahtee, 2006); a case study on research-design model courses for professional development of high school physics teachers in physics education(Eylon & Bagno, 2006); evaluation of college students' perceptions of a physics teacher's PCK development (Jang, 2011).

Stage three was the disturbance period (2012–2016). This stage saw the publication of 35 articles, with a total citations of 873. Key research topics included PCK, TPACK, teacher knowledge, science teachers, framework and physics. Notable studies included research on physics teachers' PCK characteristics (Alonzo et al., 2012); pre-service physics teachers' PCK (Milner-Bolotin et al., 2016; Riese et al., 2015); university physics teachers' TPACK and PCK (Chang et al., 2015; Jang & Chang, 2016; Jang et al., 2013; Kirschner et al., 2016; Yeh et al., 2014). Research during this stage covered primary, secondary, and tertiary education levels, enriching and refining the theoretical framework of physics PCK. Generally speaking, the research at this stage covers a wide range of topics, and there are not many papers published every year.

Stage four was the research burst phase (2017–2018). In this phase, 28 articles were published, with a high number of papers per year and a total citations of 447. Key research topics included PCK, science, education, physics, science educaton. These literatures had both research on physics teachers' PCK and research on students' physics learning. Notable studies included research on physics teachers’ PCK (Caleon et al., 2018; Krzywacki et al., 2017; Melo-Niño et al., 2017); pre-service physics teachers’ PCK (Gürel & Süzük, 2017; Kulgemeyer & Riese, 2018; Zhou & Xiao, 2018); effects of PCK in physics learning (Balukovic et al., 2017; Kao et al., 2017; Keller et al., 2017; Rollnick, 2017; Zhou & Xiao, 2018). Physics PCK research on this stage included both theoretical studies and empirical studies. Of course, some scholars' physics PCK research has been ongoing before 2017, but the paper was published in 2017-2018. For example, Jasmina Balukovic's article (Balukovic et al., 2017) was submitted in May 2016, received in July 2016, and published in May 2017.

Stage five was the steady-state period (2019–2023). In this phase, 44 articles were published, with a total citations of 239. Key research topics included PCK, edecation, teacher education, science, beliefs, physics, achievement, professional development, professional knowledge and content knowledge. PCK research expanded further to include both theoretical model constructions and empirical studies in educational teaching. Examples included pre-service physics teachers' professional knowledge, digital media PCK and PCK (Agyei et al., 2019; Kulgemeyer et al., 2020; Schiering et al., 2021; Schiering et al., 2023; Schubatzky et al., 2023; Sorge, Keller, et al., 2019; Sorge, Kröger, et al., 2019), physics teachers' knowledge and PCK (Kotoka & Kriek, 2023; Liepertz & Borowski, 2019; Marake et al., 2022; Mazibe et al., 2020). This phase saw a refinement and deepening of research, encompassing macro-level theoretical studies and micro-level investigations based on classroom teaching and specific physics concepts and principles.

5. Limitations

This systematic review should take into account its limitations. First, relying solely on a single database such as Web of Science may not capture the full breadth of relevant publications. Because only peer-reviewed articles indexed in Web of Science were reported on, there is an inherent risk that the coverage is not comprehensive enough. This means that some pertinent works may have been overlooked, which could have provided additional perspectives on physics PCK. This approach may lead to a distorted view of the research landscape, because it may not have been fully represented the comprehensive scope of research activities in this domain. Furthermore, the rough division of physics PCK research stage may not be accurate. In addition, the bibliometric analysis in this paper was conducted in Jan 2024. With the rapid development of physics PCK research,it is possible that some of the latest research literature will not be included in the bibliographic database when this paper is published, which may lead to the lack of cutting-edge literature. In the future, we will widen our database search to find more objective and verifiable bibliometric methods and tools so that we can enhance the results of this paper. Furthermore, considering the close relationship between physics and other natural sciences (such as chemistry, biology, etc.), future studies are recommended to analyze the data of PCK of chemistry, biology and other disciplines.

6. Conclusion

Despite these limitatons above, this study is the first of its kind to draw the knowledge mapping of physics PCK research. This study provides a comprehensive bibliometric analysis of the research on physics PCK since the 21st century. The results reveal a sustained scholarly interest in this topic.

The annual publication trends, keyword clustering, and research hotspots revealed that the evolution of physics PCK research progressed through five distinct stages: slow development period (2000–2005), slow progress period (2006–2011), disturbance period (2012–2016), burst period (2017–2018) and steady-state period (2019–2023).

The results show that researchers in this field have covered a wide range of topics, seven of which are particularly highlighted. The hot topics of physics PCK research mainly included pre-service physics teacher, pedagogical content knowledge, knowledge acquisition, science educaiton, understanding energy, knowledge acquisition, classroom practice, and coping strategies. These research involves the development, characterization and measurement of physics PCK for pre-service and in-service physics teachers.

The results identified an emphasis on constructing theoretical models of physics PCK, such as characterisations of physics PCK, with a focus on quantitative research and empirical studies, including case studies and experimental research.

The limitation of this study is that the data comes from a single database. Of course, there are many literature about physics PCK. Therefore, future studies should use other databases (such as EBSCO host, Scopus) to retrieve physics PCK literature. Furthermore, considering the close relationship between physics and other natural sciences (such as chemistry, biology, etc.), future studies are recommended to analyze the data of PCK of chemistry, biology and other disciplines.

The trends in publication and citation data show that research interest in physics PCK is and will continue to grow in general. Scholars can collaborate with others and seek to communicate with influential researchers or communities in this field, which is beneficial to both innovation and creation. Physics teachers and educational researchers should learn from and adapt the theoretical outcomes and advanced experiences of international physics PCK research. Moreover, this should be integrated with practical implementation of PCK research aligned with curriculum reform to provide effective methods to advance physics curriculum reform and achieve high-quality development in physics education.

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