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Review Article

A decade of TPACK in science education: Trends and insights from bibliometric analysis

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The Industrial Revolution 4.0 necessitates the integration of digital technology into education, which emphasizes the importance of Technological Pedagogical Content Knowledge [TPACK] for teachers. This research presents information related to trend analysis, which focuses on TPACK studies in science learning. Nevertheless, it also provides information on writer productivity based on Lotka Law and journal distribution patterns based on Bradford's Law, which has yet to be discussed in previous articles. This study uses bibliometric analysis to examine the research trends of TPACK in science education from 2013 to 2023, using data from Scopus and tools such as bibliometric packages R and VosViewer. Findings indicate a growing interest in TPACK, with increasing annual publications, significant contributions from authors such as Namdar and Huwer, and high-impact journals such as the Journal of Research in Science Teaching. In addition, this article presents the author's productivity based on Lotka's Law. Key themes include integrating technology in teaching practices and the role of TPACK in improving science education. This analysis highlights influential articles and authors, offers insights into the evolution and impact of TPACK research, and guides future studies in this critical area of education.

Keywords: Bibliometric; Science education; TPACK; Trends

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1. Introduction

The Industrial Revolution 4.0 has directed all aspects of life toward the application of digital technology, artificial intelligence, extensive data analysis, and robotics. This also includes the field of education, where Education 4.0 emphasizes integrating cyber technology into the learning process. Teachers must have skills in using technology as an integral part of learning, reflected in the Technological Pedagogical Content Knowledge [TPACK] (Chai et al., 2013; Mouza et al., 2014). TPACK is a theoretical framework that combines technology, learning approaches, and subject matter in a learning context, which is very relevant to the Industrial Revolution 4.0 (González-Pérez & Ramírez-Montoya, 2022; Shafie et al., 2019). TPACK skills are essential for aspiring teachers as they are responsible for teaching various subjects. Prospective teachers with TPACK

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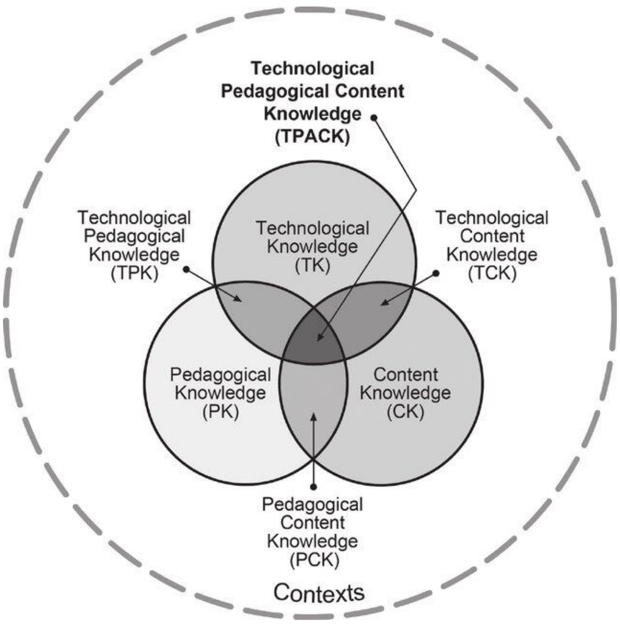
competency can combine technology with learning materials and teaching strategies that suit students' needs (Agyei & Voogt, 2015; Tondeur et al., 2020). Integrating technology into the learning process offers substantial advantages for students, particularly in grasping mathematics and science concepts, which are frequently abstract. The task of teachers and prospective teachers is to change abstract learning into more concrete, relevant, and appropriate to student's level of thinking by using technology (Ertmer & Ottenbreit-Leftwich, 2010; So & Kim, 2009). Effective teachers are expected to be able to utilize technology optimally to enrich students' understanding, foster interest in learning, and improve students' skills.

TPACK serves as a framework for educational researchers and practitioners to design and refine learning models that enhance the achievement of learning objectives through more effective processes. It emphasizes that educators, including current and future teachers, must integrate and develop a strong foundation in technology, pedagogy, and content knowledge to deliver successful teaching outcomes (Angeli et al., 2016; Hughes, 2005). Although TPACK is crucial, there has been limited effort to gather data on its global scientific production. TPACK is a teacher knowledge and skills concept that Shulman first put forward in 1986-1987 (Koehler & Mishra, 2009). This concept summarizes teachers' understanding of technology, education, and learning subjects and their application in learning contexts. Furthermore, research led by Shulman (1987) explained the elements that influence TPACK in more depth, including TK, CK, PK, PCK, TCK, and TPK. These elements then form the TPACK framework, depicted visually in Figure 1.

Figure 1
Framework of TPACK (Source: http://TPACK.org/)



In developed countries, teacher competence is recognized as TPACK, comprising three key elements: Pedagogical Knowledge [PK], Content Knowledge [CK], and Technological Knowledge [TK]. These components combine to create a subject-specific pedagogy, which includes TPK, TCK, and PCK, all together forming the TPACK framework. The TPACK model has been widely used by education and educational technology researchers globally, generating interest in technology integration (Dalal et al., 2017; Wang, 2022). The TPACK model has recently gained attention within the educational research community, evidenced by the increasing number of special interest groups and the rising frequency of TPACK discussions at educational conferences and associations. Many researchers recognize the potential and broad appeal and potential of the TPACK model. The TPACK framework is very relevant in science education because it integrates technological, pedagogical, and content knowledge in science learning (Lin et al., 2013; Mai & Hamzah, 2017; Tanak, 2020). In science education, TPACK allows teachers to effectively integrate technology in teaching science material, design learning strategies that suit the characteristics of science material, and consider students' needs in the learning process. Thus, TPACK is a tool for integrating technology into science learning and a framework that facilitates more meaningful, relevant, and in-depth learning for students (Baran & Uygun, 2016; Graham et al., 2012; Santos & Castro, 2021). Seeing how vital TPACK is in today's education, one approach researchers apply is to carry out literature searches using bibliometric analysis.

Several previous studies conducted bibliometric studies related to TPACK, such as TPACK trends (e.g., Lee et al., 2022; Suprapto et al., 2021; Zou et al., 2022), TPACK Instruments (Muhlis et al., 2023), Impact of TPACK (Simangunsong et al., 2024), TPACK framework (e.g., Putri et al., 2022; Rodríguez Moreno et al., 2019), and TPACK in Chemistry Education (Marlina et al., 2023). However, this research presents information related to trend analysis and focuses on TPACK studies in science learning. However, it also provides information on writer productivity based on Lotka Law and journal distribution patterns based on Bradford's Law, which has not been discussed in previous articles. Therefore, bibliometric analysis is needed to reveal this information.

Bibliometric analysis is an effective method for evaluating the impact of a paper on the progress of science. Bibliometric indicators such as research field, document sources, publication output, language sources, country and institution distribution, primary authors, number of citations, and author keywords are often used to analyze research trends. This research aims to identify trends in TPACK research in the context of science education over the last decade to help educational researchers understand the global picture regarding TPACK. In this research, the researchers explored various parameters or relationships between variables in TPACK, such as TPACK products, research design methods used, the relationship between TPACK and science education, the most influential researchers in the TPACK field, and policies related to TPACK. Therefore, the focus of this research is to analyze TPACK in science education with the following questions:

RQ 1) What is the main information about TPACK in science education?

RQ 2) What are the top profiles of authors TPACK on science education?

RQ 3) What are the most productive countries and affiliations of TPACK on science education?

RQ 4) What are the keyword trends and their visualizations mapping TPACK on science education?

RQ 5) What is the review of top-cited articles of TPACK on science education?

2. Literature Review

2.1. Technology Pedagogical Content Knowledge

The TPACK framework builds on Shulman's (1986, 1987) concept of Pedagogical Content Knowledge [PCK] by exploring the interaction between teachers' knowledge of educational technologies and their PCK, which supports effective technology integration in teaching. While other researchers have explored related concepts under different names, the TPACK framework has been refined and expanded over time. The most detailed articulations can be found in several works (e.g., Koehler & Mishra, 2009; Mishra & Koehler, 2006). Teachers' knowledge comprises three core components: content, pedagogy, and technology (see Figure 1).

Content knowledge refers to a teacher's understanding of the subject matter that needs to be taught or learned (e.g., Kind & Chan, 2019; Kleickmann et al., 2013; Koehler & Mishra, 2009). For instance, the content in a secondary school science or physics course differs significantly from that in a college-level course, with the complexity and depth increasing as the educational level advances. Mastery of content is crucial for educators. As Shulman (1986) highlights, this encompasses understanding key concepts, theories, ideas, organizational structures, evidence, and validation, along with the established methods and practices used to generate this knowledge. The nature of inquiry varies significantly across different disciplines, requiring teachers to deeply grasp the knowledge bases specific to the subjects they teach. In the case of science, for instance, this includes familiarity with scientific facts and theories, the scientific method, and evidence-based reasoning (e.g., Bayram-Jacobs et al., 2019; Schneider & Plasman, 2011). The lack of a solid foundation in content knowledge can be costly. For instance, students may need to be given more accurate information and develop misunderstandings about the subject matter (e.g., Nilsson & Van Driel, 2011; Yates et al., 2014).

Pedagogical knowledge (PK) refers to a teacher's comprehensive understanding of the processes, practices, and methodologies involved in teaching and learning (e.g., Gess-Newsome., 2019; Lachner et al., 2019; Mishra & Koehler, 2006). This knowledge encompasses various aspects, including the broader educational objectives, values, and goals. It is a comprehensive form of knowledge that includes understanding student learning processes, expertise in general classroom management, effective lesson planning, and evaluating student performance. Additionally, it includes familiarity with classroom strategies and methods, awareness of the characteristics of the students being taught, and the ability to assess students' comprehension effectively. A teacher with extensive pedagogical knowledge grasps how students build knowledge, develop skills, and cultivate positive attitudes and habits toward learning (e.g., Appleton, 2013; Nilsson, 2008). Therefore, pedagogical knowledge requires a solid grasp of cognitive, social, and developmental learning theories and how these theories are applied to students in the classroom context (e.g., Bada & Olusegun, 2015; Hofer & Pintrich, 1997).

Technology knowledge (TK) is inherently dynamic and evolves more rapidly than the other core domains of the TPACK framework, namely pedagogy and content (e.g., Glowatz & O'Brien, 2017; Koehler & Mishra, 2009). This constant change makes it challenging to pinpoint a precise definition of TK, as any attempt to do so risks becoming obsolete by the time it is published. Despite this, specific approaches to understanding and engaging with technology remain relevant across various tools and resources. These approaches involve recognizing patterns in technological advancements and applying adaptable strategies for effectively integrating new technologies into teaching and learning practices.

2.2. Lotka's and Bradford's Law

Lotka's Law is a bibliometric principle that analyzes the distribution of scientific publications among authors. This Law, first proposed by Alfred J. Lotka (1926), demonstrates that a small fraction of authors generate the bulk of scientific literature, whereas most produce relatively few works. Lotka discovered that the number of authors publishing a certain number of works is inversely proportional to the square of the number of publications (e.g., Osareh & Mostafavi, 2011; Sahu & Jena, 2022). Mathematically, this Law is expressed as:

$$A(n) \propto \frac{1}{n^2}$$

Where:

- $A(n)$ is the number of authors with n publications
- n represents the number of publications.

In practical terms, if 100 authors have a single publication, then approximately 25 will have two publications, about 11 will have three, and so forth.

Bradford's Law, a bibliometric principle formulated by Samuel C. Bradford (1934), explains the distribution of articles on a specific subject across different academic journals. The Law posits that a small set of core journals will account for most articles on a particular topic. In contrast, more journals will each contribute fewer articles, and an even more significant number will contain only a tiny portion. This distribution results in a Bradford pattern, where the number of journals is inversely proportional to the volume of articles they publish. Bradford's Law illustrates the concentration of scholarly work in a few key journals and the relative scarcity of relevant articles in the remaining journals (e.g., Meller et al., 2023; Shenton & Hay-Gibson, 2009).

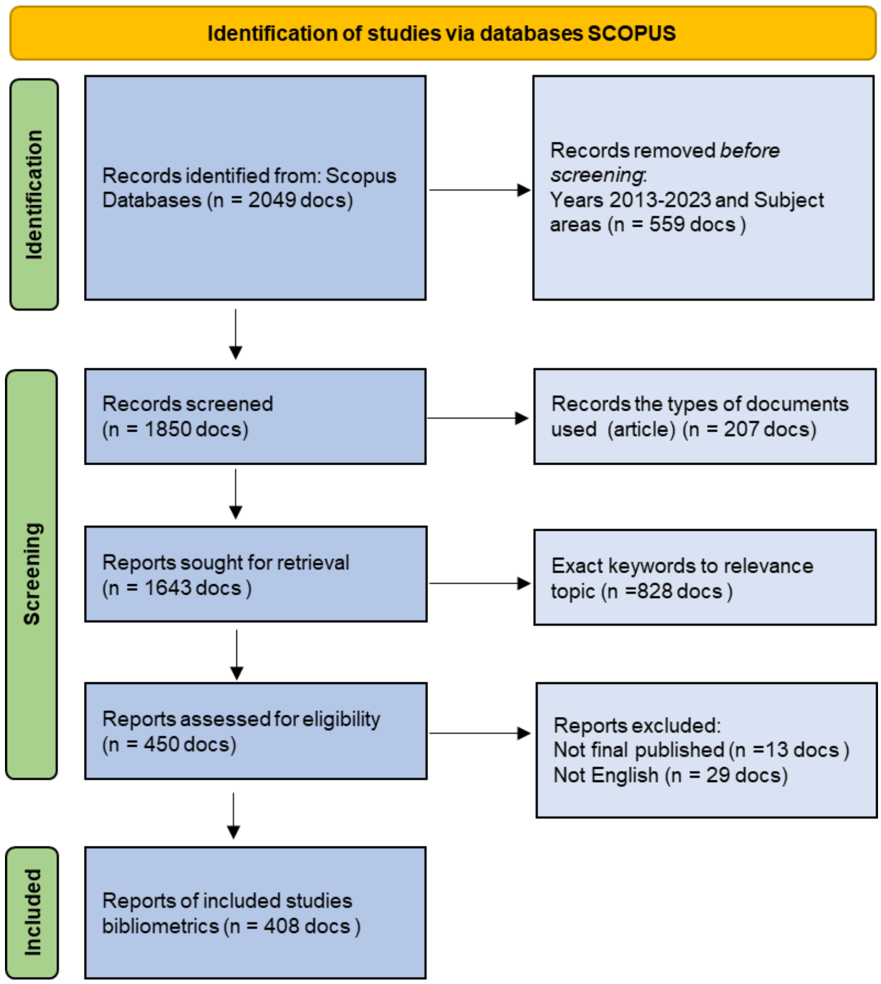
3. Method

This research used bibliometric methods to identify and describe research trends in the TPACK domain in science education. Research trends reflect researchers' collective interest in a particular topic and are considered indicators of the match between contemporary scientific findings and societal needs (Klavans & Boyack, 2017; Wagner et al., 2011). Bibliometric analysis allows a better understanding of intellectual relationships in dynamic scientific knowledge systems (Gaviria-Marin et al., 2018; Prahani et al., 2022). This helps researchers identify potential future research paths. To perform bibliometric analysis, access is required to bibliographic databases that provide essential information about scientific publications, such as title, author, abstract, keywords, and references. Scopus is a database often chosen because it extensively covers scientific journals, conferences, and books globally and regionally. The advantage of Scopus also lies in its strict selection and indexing process, which ensures the high quality of the data provided (Ball & Tunger, 2006; Pranckutė, 2021). In addition, Scopus offers support for multiple formats and platforms for conducting data analysis.

3.1. Data Collection

Research data was collected on April 30, 2024, using a set of general criteria for data searches. These criteria include keyword combinations using binary operators such as OR and AND. The keywords chosen for data collection were (TITLE-ABS-KEY ("Technological Pedagogical Knowledge" OR "Technological Knowledge" OR "Technological Content Knowledge") OR ("Pedagogical Knowledge" OR "Content Knowledge") AND ("Science Education"). Data was then filtered based on the title, abstract, and author keywords. Data collection was limited to research published between 2013-2023, and the articles used were final. They were then processed using the R bibliometric package and Vosviewer. The details are presented in Figure 2.

Figure 2
Article selection flowchart



3.2. Data Analysis and Visualization

Science mapping is a visual representation that shows trends and relationships between various scientific fields, documents, or authors in a research domain in a spatial format. Through this mapping, it can be understood how various topics and concepts are related to each other, as well as how various authors and journals have contributed to the development of the field. Thus, science mapping helps identify the patterns and dynamics underlying the development of knowledge in a field and provides a more comprehensive view of the structure and evolution of research (Chen, 2017). This research uses bibliometric analysis and bibliographic data to identify, analyze, and understand patterns in scientific literature. The main goal is to understand research developments, topic trends, collaboration networks between researchers, and the impact of publications in a knowledge domain. Using bibliometric analysis, researchers can identify emerging research areas, evaluate research productivity and impact, and direct future research directions. Additionally, the R package with the Biblioshiny, Excel, and VosViewer programs was used to visualize the database mapping results that had been downloaded on the Scopus page (Amiruddin et al., 2023; Ejaz et al., 2022; Van Eck & Waltman, 2010, 2017). A summary of the primary information from this study is presented in Table 1.

4. Result

4.1. The Main Information of TPACK on Science Education

Table 1 presents important information from the Scopus database regarding the development of TPACK in science learning from 2013 to 2023.

Table 1
Main information of TPACK on science education

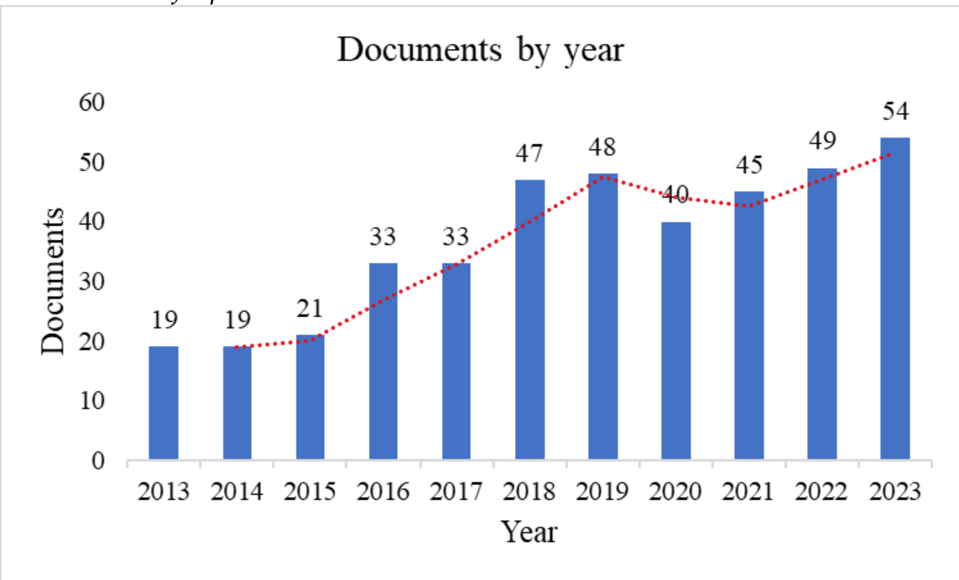
Description	*Results*
Main Information About Data	
Timespan	2013:2023
Sources	143
Documents	408
Annual Growth Rate %	11,01
Document Average Age	5,03
Average citations per doc	15,32
References	24068
Document Contents	
Keywords Plus (ID)	394
Author's Keywords (DE)	1067
Authors	
Authors	1188
Authors of single-authored docs	46
Authors Collaboration	
Single-authored docs	48
Co-Authors per Doc	3,24
International co-authorships %	14,95
Document Types	
Article	408

The basic information listed in Table 1 shows significant year-on-year growth and meaningful impact, as reflected in the average number of citations per document. Collaboration in this field is not limited to the domestic level but is also international, reflected in the co-authorship pattern involving researchers from various countries. The percentage of international co-authorship indicates a high level of collaboration in this field of study. In addition, the work used in this research is a published article. By utilizing a variety of cross-disciplinary keywords and themes, research in this field continues to foster inventive scientific inquiry and adds value across different fields, enhancing innovation and creativity within the scientific community.

4.1.1. Annual publication production trends

Figure 3 shows that the trend of TPACK publications in science learning fluctuates gradually from year to year.

Figure 3
Annual scientific publication



From 2013 to 2019, there was an increase in article publications, as shown in Figure 2. Although there was an increase, it was not very significant (i.e., 2014 with 19 publications) whereas (i.e., 2015 with 21 publications). Then, in 2019-2020, there was a decrease in the number of publications by 8 documents. After that, in 2020-2023, there was another increase in the number of publications, reaching the highest number (i.e., 2023 with 54 publications). The publication trend is good because the decline is not too drastic. Following up on the data in Figure 2, the annual total citations per year for each published article are presented in Table 2.

Table 2
Article citation per year

Year	*Mean TC per Article*	*N*	*Mean TC per Year*
2013	**52,79***	19	**4,40***
2014	16,74	19	1,52
2015	17,43	21	1,74
2016	22,45	33	2,49
2017	15,3	33	1,91
2018	20,62	47	2,95
2019	19,69	48	3,28
2020	10,25	40	2,05
2021	14,16	45	3,54
2022	4,73	49	1,58
2023	2,3	**54***	1,15

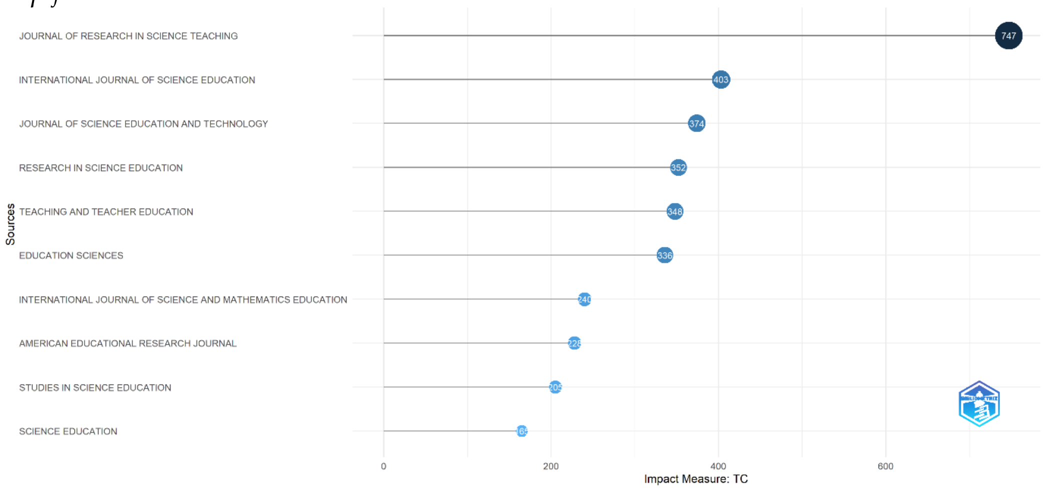
Note. TC: Total citation; *: Top.

Table 2 details the contribution of articles per year based on total citations. Based on the data in Table 2, the highest total citations per article was 52.79 in 2013, with a total of 19 documents. Meanwhile, the total number of citations per year was 4.40, also in 2013. Then, the total citations per article and year will be at least in 2023. This is predicted because the published articles are still new.

4.1.2. Total citation of journal

In the world of research and publication, one of the roles that plays a role is that of a journal as a place to publish articles. As for the TPACK field in science education, the distribution of journals with the most citations is presented in Figure 4.

Figure 4
Top journal total citation



The journal with the most citations presented in Figure 3 with the keyword TPACK on science education is "Journal of Research in Science Teaching with 747 TCs". Second place was followed by "International Journal of Science Education with 403 TCs". Moreover, third place is "Journal of Science Education and Technology with 374 TCs". Meanwhile, "Science Education" is the journal with the fewest citations, namely 165 TCs.

4.1.3. Thematic development

This section uses a Sankey Diagram to illustrate thematic developments related to keywords, authors, and countries, which are essential elements in this topic. According to Riehmann et al. (2005), Sankey diagrams are visualizations used to depict the flow from one set of values to another. The connected things are called nodes, and the connections are called links. Sankey is best used when you want to show a many-to-many mapping between two domains (i.e., keywords, authors, and country) presented in Figure 5.

Figure 5
Sankey diagram of TPACK on science education

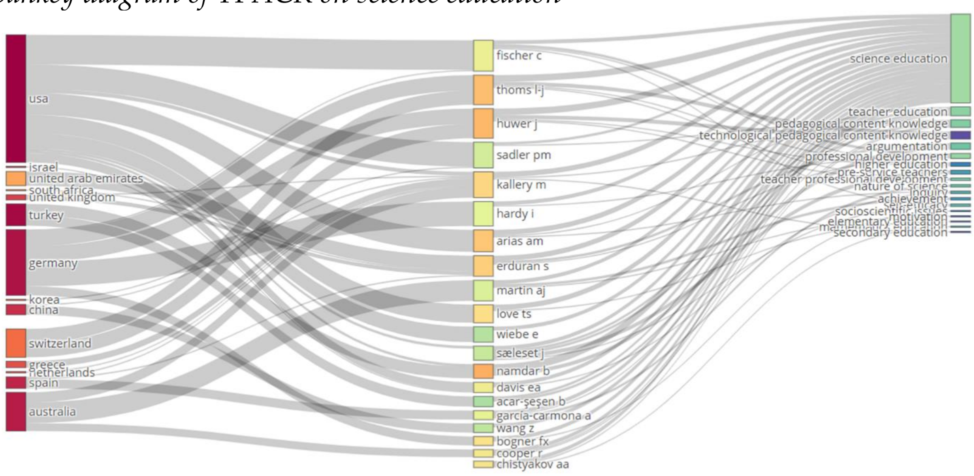


Figure 5 presents the relationship of keywords, author, and country. The most dominant keywords in Figure 5 are science education, teacher education, PCK, TPCK, argumentation, etc. The authors who have the closest ties to science education are Fischer, Thomas, and Huwer. However, the total number of existing authors is dominated by authors from Australia (i.e., Fischer, Sadler, Arias, etc.).

4.2. Research Profiles Authors and TPACK on Science Education

4.2.1. Top authors productions

There are definitely writers who are truly experts in a particular field. In this case, TPACK is useful in science learning. In this way, Figure 6 presents the top 10 author productions during 2013-2023 based on the number of documents.

Figure 6
Top author production by documents

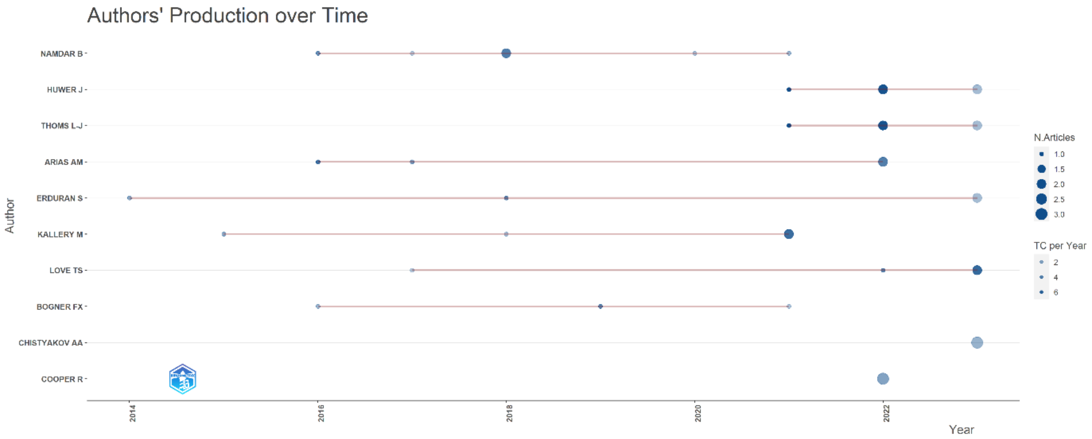
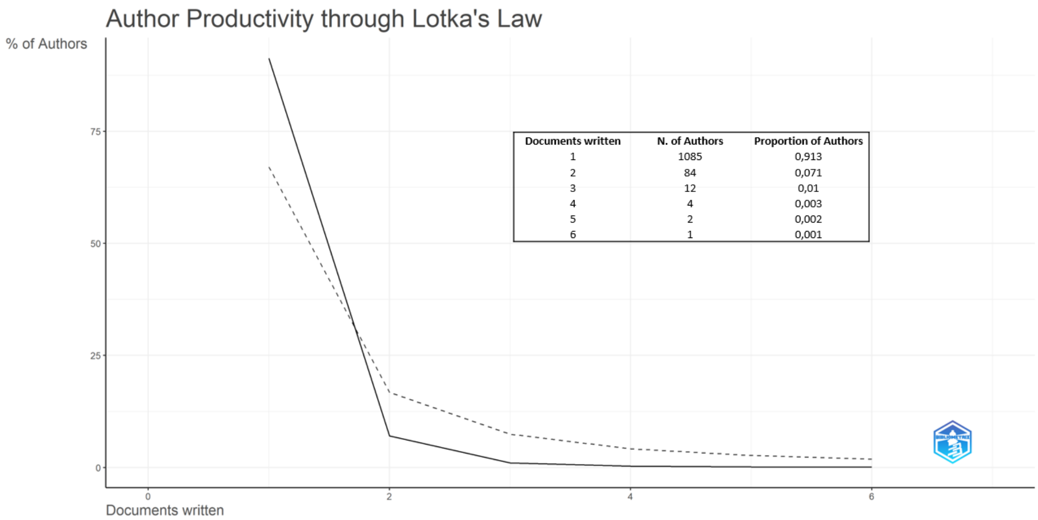


Figure 6 presents information related to the top 10 authors during 2013 – 2023 on the topic TPACK on science education. The authors who dominate this topic are Namdar (6 docs), Huwer and Thoms (5 docs), Arias, Erduran, Kallery, and Love (4 docs), Bogner, Chistyakov, and Cooper (3 docs). Lotka's Law is presented in Figure 7 to see the distribution of writer productivity.

Figure 7
Author productivity



Lotka's Law was introduced by Alfred j. Lotka (1926) refers to productivity distribution in various fields, especially in science and academic publications. Lotka's Law states that in a particular domain, the number of productive individuals in that domain will be much less than the number of less productive individuals. In the context of scientific publications, a small percentage of researchers or authors will produce the majority of significant scientific work. In contrast, the majority of people will produce little or none. In line with what is presented in Figure 6, it can be seen that 1085 authors only have 1 doc, 84 authors only have 2 docs, 12 authors only have 3 docs, and 4 authors only have 4 docs.

4.2.2. Top sources' local impact by h-index

The "h-index" is a metric used to measure the productivity and impact of a particular researcher or source in the scientific world. Torge E. Hirsch developed this metric in 2005. A researcher's or source's Index Indicates the number of scientific works the researcher has published and each work has been cited at least h-index times. In this context, it refers to journals that have an impact, as presented in Figure 8.

Figure 8
Top 10 Source local impact

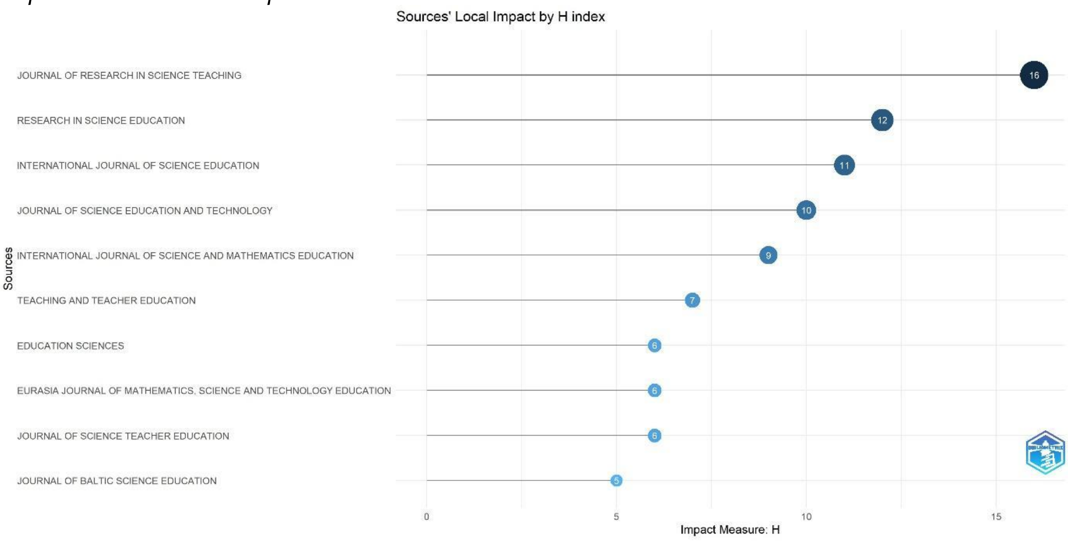
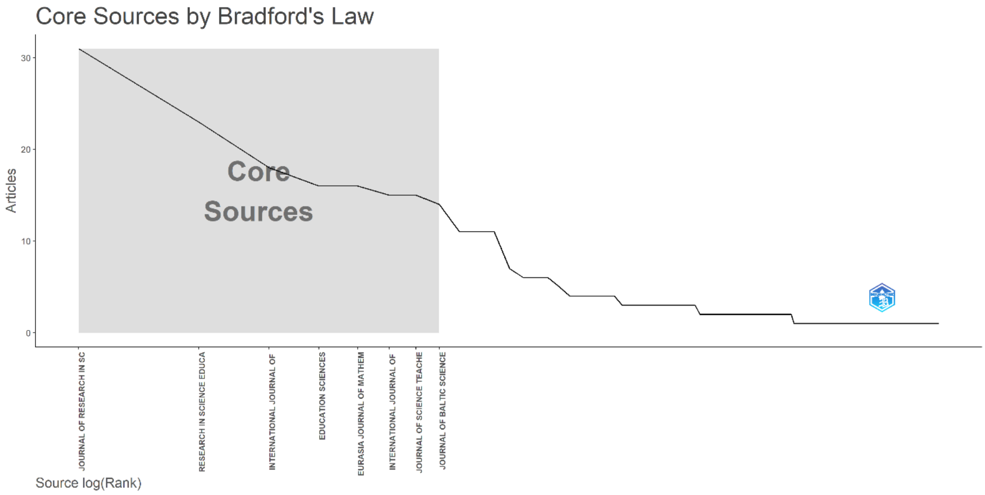


Figure 8 presents the source local impact by journal h-index. Impact journals based on the h-index are dominated by "Journal of Research in Science Education (16 docs)", "Research in Science Education (12 docs)", "International Journal of Science Education (11 docs)", "Journal of Science Education and Technology (10 docs) etc. The data presented in Figure 8 is in line with Bradford's Law, which describes the distribution pattern of journals for scientific publications in a subject or scientific discipline, which is presented in Figure 9.

Figure 9
Sources by Bradford's Law



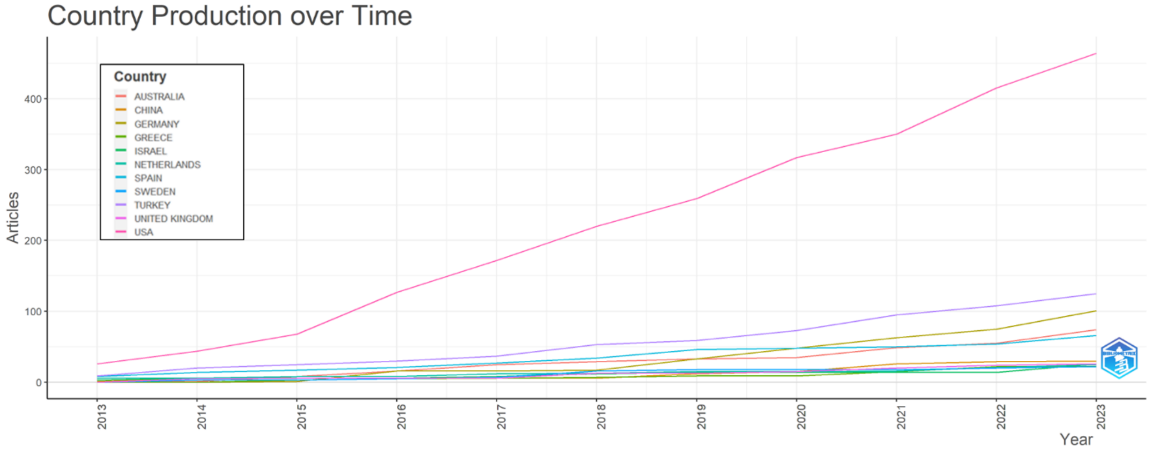
4.3. The Most Productive Countries and Affiliations of TPACK on Science Education

4.3.1. Most productive country

The state has a role related to the development of science, especially with a sound education system. The top 10 most productive countries in the field of TPACK on science education are presented in Figure 10.

Figure 10

Top productive country



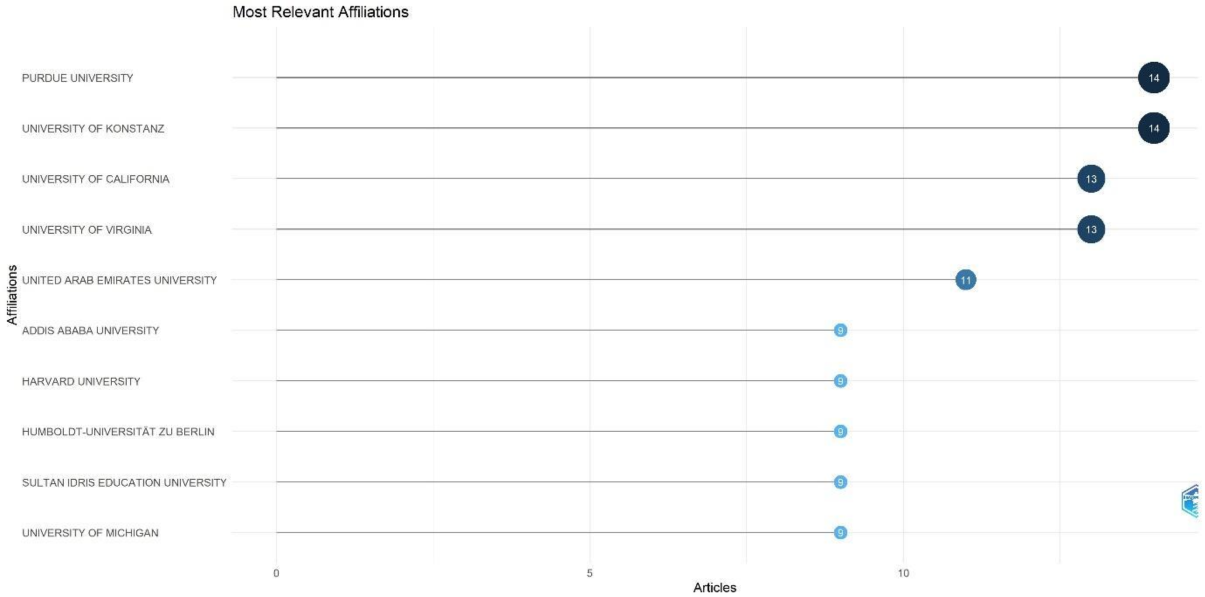
The most productive country presented in Figure 10 is the USA (2462 docs), followed by Türkiye (634 docs) and Spain (385 docs). The line presented in Figure 10 follows the number of publications each year, so what is seen is not the final line. This country's top productivity can be a reference related to TPACK in science education. This is in line with the most relevant country presented in Figure 11.

4.3.2. Most Productive Affiliation

In line with productive countries, the most productive affiliations are similar to the previous three top countries. Figure 11 presents the details.

Figure 11

The most productive affiliation



The most dominant affiliations related to the number of publications are Purdue University and University of Konstanz (14 docs), University of California and University of Virginia (13 docs), United Arab Emirates University (11 docs), and Addis Ababa University, Harvard University, Humboldt Universitat Zu Berlin, Sultan Idris Education University and University of Michigan (9 docs). However, from the data presented in Figure 11, it can be seen that there are universities originating from Malaysia (Sultan Idris Education University). It is interesting to study this more deeply because Malaysia is not included in the list of most productive countries but is one of the most relevant affiliations.

4.4. The Keyword Trends and Their Visualizations Mapping TPACK on Science Education

All keywords were used to create a map with Co-occurrence using VosViewer. The visualization results are presented in Figure 12. The researcher divided the formed map into five sections marked with numbers 1-5 written on each section.

Figure 12
Mapping keywords

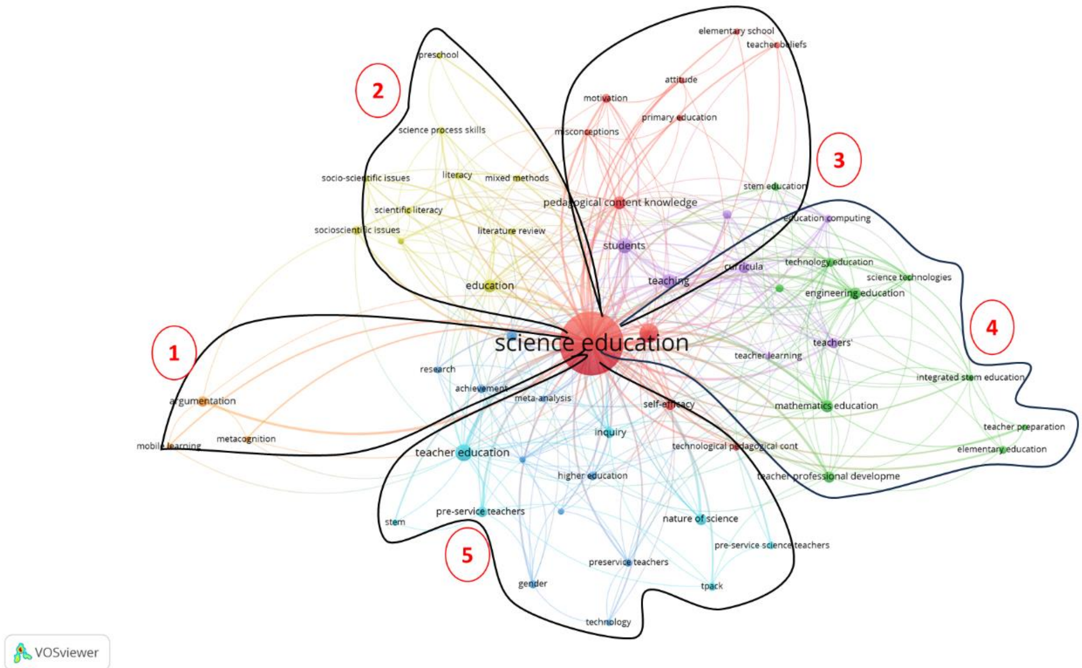
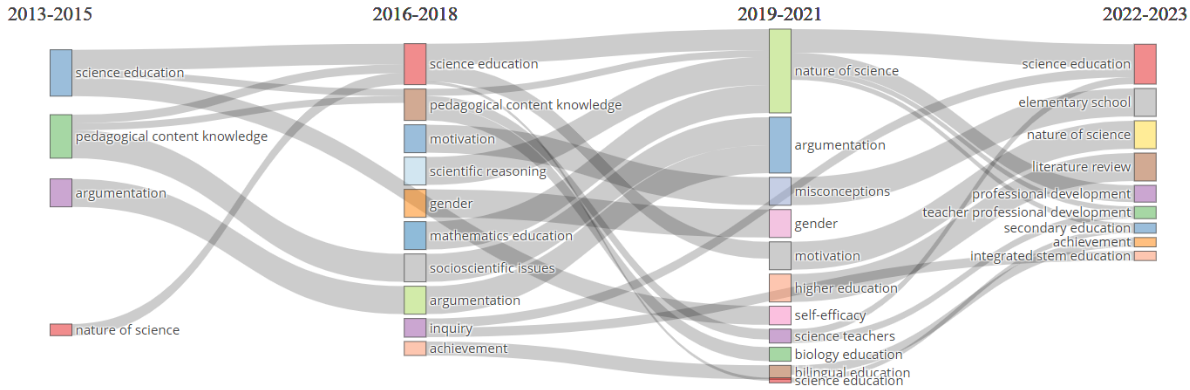


Figure 12 presents an illustration of keyword mapping divided into five parts. In cluster 1 (argumentation, metacognitive, and argumentation), researchers grouped them into modern educational contexts. This is because these three concepts have great relevance in modern education, emphasizing critical thinking skills, the use of technology, and self-understanding. Cluster 2 (Scientific literacy, literacy, socioscientific issues, etc.) is included in science and literacy because it is integral to holistic science education. Cluster 3 (Attitude, motivation, pedagogical, students, etc.) is included in the context of education and learning. Cluster 4 (Technology education, science technologies, integrated science, etc) is included in the STEM context because it emphasizes the importance of integrating science, technology, engineering, and mathematics in learning. Cluster 5 (technology pedagogical content, self-efficiency, TPACK, preservice teacher, etc.) is included in the TPACK study because it provides a framework for integrating technology into effective teaching. In detail, the keyword evolution trend based on author keywords is presented in Figure 13.

Figure 13
Author keyword evolution



The author's keyword in evolution from 2013-2023 is the most consistent: "Science education." This is proven by the appearance of these keywords every year they appear. Apart from that, PCK has a close relationship, although it does not always appear yearly, and there are intersections between them. Apart from that, the word "Argumentation" from 2013-2021 continues to appear, but in 2022-2023, it has no connection with other keywords. Meanwhile, the keyword "Nature of science" intersects with science education, then with the nature of science, and then back to education.

4.5. Most Global Top-Cited Articles of TPACK on Science Education

One indicator of publication quality is the number of citations received by published articles. Table 3 presents the top-cited articles in the field of TPACK on science education during 2013-2023.

Table 3 presents the top cited articles in TPACK on science education 2013-2023. The author of the article with the highest number of citations is Kalogiannakis et al. (242 cited), Sadler et al. (228 cited), Zohar and Barzilai (205 cited), Fauth et al. (168 cited), Jaipal-Jamani and Angeli (149 cited), Zamora-Polo et al. (120 cited), Russ and Luna (95 cited), Manz and Suárez (95 cited), Clarke et al. (88 cited), and Brigido et al. (87 cited). These authors publish their work in reputable journals indexed by Scopus. The available DOI can be used to explore the article's details.

5. Discussion

Essential information related to the TPACK framework plays a vital role in shaping science education by emphasizing integrating technology, pedagogy, and content knowledge. In this case, one thing that can be done is to trace research developments related to TPACK in science education. Through valid information, it can be seen how many documents, keywords, and author collaborations are carried out in that field. In the context of science teaching, TPACK requires a deep understanding of how to effectively utilize a variety of technological tools, such as simulations, multimedia resources, and data collection tools, to convey scientific concepts to students (Jimoyiannis, 2010; Maeng et al., 2013; Yeh et al., 2014). This understanding is complemented by pedagogical knowledge, which involves using effective teaching strategies and methods tailored to the needs of science students, including classroom management and assessment techniques.

Additionally, a strong foundation in content knowledge is essential, covering basic scientific principles and recent developments in various scientific fields (Harris et al., 2009; Koehler & Mishra, 2009). TPACK also highlights the importance of pedagogical content knowledge, which involves the skillful integration of pedagogical strategies with content knowledge to facilitate meaningful learning experiences for students (Koehler et al., 2013; Santos & Castro, 2021). TPACK provides science educators with a comprehensive framework for integrating technology into their teaching practices to increase student engagement, understanding, and achievement in science education.

Table 3

Top ten cited articles

Rank	*Paper*	*DOI*	*Total Citations*	*MC*	*Source*
1	Kalogiannakis et al. (2021)	10.3390/educsci11010022	242	60.50	EDUC SCI
2	Sadler et al. (2013)	10.3102/0002831213477680	228	19.00	AM EDUC RES J
3	Zohar & Barzilai (2013)	10.1080/03057267.2013.847261	205	17.08	STUD SCI EDUC
4	Fauth et al. (2019)	10.1016/j.tate.2019.102882	168	28.00	TEACH TEACH EDUC
5	Jaipal-Jamani & Angeli (2017)	10.1007/s10956-016-9663-z	149	18.63	J SCI EDUC TECHNOL
6	Zamora-Polo et al. (2019)	10.3390/su11133533	120	20.00	SUSTAINABILITY
7	Russ & Luna (2013)	10.1002/tea.21063	95	7.92	J RES SCI TEACH
8	Manz & Suárez (2018)	10.1002/sce.21343	95	13.57	SCI EDUC
9	Clarke et al. (2016)	10.1016/j.lcsi.2016.01.002	88	9.78	LEARN CULT SOC INTERACT
10	Brígido et al. (2013)	10.1080/02619768.2012.686993	87	7.25	EUR J TEACH EDUC

Note. MC: Mean citations per year.

Apart from highlighting the importance of TPACK in science learning, it is necessary to know about publication trends in this field. The research trends presented from 2013-2023 experienced ups and downs. However, the fluctuations in the number of documents were not very significant. In 2019-2020, there was a slight decrease in the number of publications triggered by the COVID-19 pandemic, which changed the educational landscape and had to adapt quickly. From 2020 to 2023, more in-depth research will be conducted on measuring and evaluating teacher TPACK in science contexts. This includes the development of assessment instruments and an evaluation framework to measure the level of understanding and application of TPACK in science teaching (Akyuz, 2018; Schmidt et al., 2009). This period was essential for collaboration and exchange of best practices in developing TPACK in science education. According to McDaniels et al. (2016), online forums, webinars, and international conferences allow educators and researchers to share knowledge, experiences, and the best strategies for integrating technology into science learning. Thus, research from that year continued to increase and provided significant changes in the use of technology for learning. In addition, it also indicates that the use of technology in science education is becoming increasingly important, and efforts to develop understanding and application of TPACK in this context are becoming more focused and integrated (Aktaş & Özmen, 2020; Dewi et al., 2021).

Profile articles that have several citations also have an influence, in this case, on other research. According to Trajtenberg (1990), articles with many quotations indicate that the article is in line with current research. The most cited articles were in 2013 (52.79 citations per article). Meanwhile, most articles will be in 2023 (54 docs). Studies related to TPACK in science education are predicted to continue to develop based on distribution patterns in the last five years. In addition, the journal plays a role in publishing high-quality work. This can be seen based on the journal's number of citations in a particular field of study. Journals with many citations indicate that the journal is of good quality, making it a reference for researchers (Bornmann, 2008; Seglen, 1997). According to Baas et al. (2020), Chavarro et al. (2018), and Pranckutė (2021), journals that Scopus and Web of Science should index world researchers target because they have quality and a strict review process.

The development of this research can also be analyzed using the Sankey diagram. According to Lupton and Allwood (2017), Riehmann et al. (2005), and Yang and Sianturi (2021), Sankey diagrams are the result of data visualization that is used to describe the flow or transfer of information through a system. The Sankey Diagram in this research is the relationship between the study topic, researcher, and country. By using different lengths and widths of lines representing the relative amounts or proportions of flow between different parts or phases in a system, Sankey diagrams make it possible to intuitively see the relationships between input, output, and movement in a process. Based on the Sankey Diagram (see Figure 5), we can see that the most dominant topic is science education, with the author Fisher coming from the USA. The diagram can help make better decisions in designing, optimizing, and deciding on research related to TPACK on Science education.

On the other hand, the contribution of researchers or writers plays a role in a related field, and some writers dominate the topic of TPACK in science education. Writers with high productivity usually pursue this field more deeply than others. From 2013 to 2023, Namdar (6 docs) was the most dominant author. However, the productivity of writers can also be seen and analyzed through the Lotka Law introduced by Lotka (1926), which refers to the productivity of writers in the TPACK study on science education. According to Sudhir (2013), Lotka Law shows writers' productivity and can also map the distribution of articles on related topic studies. Based on Figure 6, the more works written, the fewer the authors are. This indicates that a more profound research focus will have fewer researchers but can contribute more, for example, in the number of articles.

Applying Bradford's Law to the data in Figure 9 shows the uneven distribution of scientific publications in the field of TPACK in science education. The dominance of specific journals indicates that the leading and most influential research is often published in journals with a high H-index (e.g., Hunt et al., 2010; Koltun & Hafner, 2021; Xu et al., 2015). This indicates a concentration of knowledge in core journals with a significant reputation and influence in their field. These journals are the main source for researchers for references and the main medium for disseminating essential research findings. This concentration makes it easier for researchers to find relevant research. However, it also poses challenges in diversifying knowledge sources and accessibility for researchers from institutions who may not have access to expensive subscription journals.

The United States leads in the number of TPACK-related publications in science education, indicating the country's dominant role in research and development. The high number of published documents reflects a strong focus on integrating technology in science education, with many institutions and researchers actively contributing to the global literature (Lightfoot et al., 2013; Meyer, 2000; Mirtl et al., 2018). Türkiye and Spain also demonstrated significant productivity, indicating substantial efforts in adopting and developing the TPACK concept in educational contexts. The dominance of these countries can be used as a reference for researchers and other practitioners who want to understand the development and application of TPACK in science education. The high relevance shown in Figure 10 supports that these countries are productive and influential in disseminating knowledge and best practices in integrating technology into science education. All-inclusive, the data from Figure 10 and Figure 11 show that research on TPACK in science education has a varied global distribution, with some countries playing a significant role in advancing and disseminating knowledge in this area.

This suggests that some institutions in countries that could be more productive overall can still significantly impact certain areas. For instance, Sultan Idris Education University has succeeded in making itself relevant on the topic of TPACK in science education through influential publications. This may be due to the university's strategic focus on educational research, international collaboration, or technology development initiatives in teaching. This fact highlights that significant contributions to a research field can come from more than just countries with many publications. Certain institutions can stand out and contribute significantly to developing and disseminating knowledge in specific fields through quality research and effective collaboration (Tan, 2016). It also shows the importance of supporting research at universities that have high potential to contribute to a particular scientific field, regardless of the productivity of their country of origin.

An in-depth analysis of the keyword illustrations presented in Figure 12 reveals several exciting things. Grouping concepts into clusters or thematic groups provides a clear understanding of the focus and relevance of each concept in the educational context. For instance, the first cluster highlights the importance of critical thinking skills and the use of technology in modern education. In contrast, the second cluster emphasizes the importance of scientific literacy in holistic education. Furthermore, this analysis also highlights the relationship between different concepts in the educational context. For example, integrating technology in effective teaching (in the fifth cluster) can be linked to the importance of technological literacy and pedagogical skills (in the fourth cluster). In addition, this grouping also highlights a holistic approach to education, as seen in the second cluster, which highlights the importance of scientific literacy, including social and scientific issues, as an integral part of science education. Thus, this analysis not only provides an overview of the main focus of TPACK on science education but can also present future research opportunities through link correlation and the size of the VosViewer visualization results (e.g., Sood et al., 2021; Van Eck & Waltman, 2017; Yang & Thoo, 2023).

Additionally, the number of citations an article receives reflects the recognition and relevance of the work within the academic community (Serenco & Dumay, 2015). Authors with the highest number of citations, such as Kalogiannakis (242 citations), Sadler (228 citations), and Zohar (205 citations), show that their research has had a significant impact on the field of TPACK in science education. The high number of citations also indicates that their works are often referred to as essential references in other studies, indicating their substantial contribution to the development of knowledge in this field (e.g., Bornmann et al., 2012; Bornmann & Daniel, 2008; Tahamtan et al., 2016). The publication of articles in reputable journals indexed in Scopus shows that the research has undergone a strict assessment process, and experts in the field have recognized its quality. This adds credibility and trust to the findings and methodology used by the authors. According to Ghazavi et al. (2019), articles published on Scopus are good quality and become references for other research. In addition, the varying distribution of citations, ranging from 242 to 87 citations, shows diversity in the impact of the research but remains within a range that shows significant relevance because it is in the top 10 in the field of TPACK on science education. Despite having fewer citations (95 citations), authors such as Russ and Manz are still considered necessary in their contributions to TPACK research in science education.

Available Digital Object Identifier [DOI] analysis can be used to drill down into further details of articles, which can provide deeper insight into each study's topic, methodology, and specific findings. Through DOI, researchers and practitioners can access original articles to understand better how each work contributes to developing theory and practice (Gerstner et al., 2017; Tauxe et al., 2016). Overall, the most cited articles in TPACK in science education during 2013-2023 are works that are highly influential and recognized in the academic community. This recognition is not only through the number of citations but also through publication in reputable journals. In this way, the results of this study show that research in this field continues to develop and contributes significantly to the understanding and practice of science education.

6. Conclusion

In conclusion, the bibliometric analysis of TPACK research in science education from 2013 to 2023 underscores the increasing relevance and impact of integrating technology into educational practices. The study reveals a consistent growth in TPACK-related publications, with notable contributions from leading researchers and high-impact journals. The evolving themes highlight the significance of TPACK in enhancing science education, emphasizing the need for educators to blend technological, pedagogical, and content knowledge adeptly. The findings provide a comprehensive overview of the research landscape, identifying key trends, influential works, and productive collaborations, thereby offering valuable guidance for future research directions in the effective integration of technology in education.

The study of TPACK in science education has theoretically and practically significant implications. Theoretically, it underscores the importance of integrating technology, pedagogy, and content knowledge to enhance teaching effectiveness, aligning with TPACK's framework for effective teaching. Practically, it highlights the growing importance of technology in education, suggesting that educators need continuous professional development to use technological tools in science teaching effectively. It also emphasizes the need for collaboration and research on best practices, which can guide educators in improving their teaching strategies and adapting to evolving educational technologies.

7. Recommendations

Based on the findings of this bibliometric analysis, it is recommended that future research in TPACK and science education continue to explore innovative strategies for integrating technology into teaching practices. Educational institutions should prioritize professional development programs that enhance teachers' TPACK competencies, ensuring they are well-equipped to meet the demands of modern education. Fostering international collaborations and cross-disciplinary research can further enrich the field, promoting the exchange of best practices and novel insights. Policymakers and educators should also focus on developing robust frameworks and resources that support the practical application of TPACK in classrooms, ultimately enhancing the quality and effectiveness of science education.

8. Limitations

One limitation of this study is its reliance on the Scopus database, which, while comprehensive, may only encompass some relevant literature on TPACK in science education, potentially omitting influential studies published in non-indexed journals or other databases. Additionally, the bibliometric analysis focuses on quantitative metrics such as publication and citation counts, which may need to capture the research's qualitative impact or practical applications fully. The study's timeframe, limited to publications from 2013 to 2023, may also need to look into earlier foundational works or recent emerging trends. Finally, the analysis needs to delve deeper into the contextual factors influencing TPACK implementation across different educational settings, which could provide a more nuanced understanding of its practical challenges and benefits.

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