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VISUALISATION ANALYSIS OF PROJECT BASED LEARNING IN MATHEMATICS EDUCATION: A BIBLIOMETRIC STUDY

(*Analisis Visualisasi Pembelajaran Berasaskan Projek dalam Pendidikan Matematik: Satu Kajian Bibliometrik*)

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ABSTRACT

This study aims to conduct a comprehensive bibliometric and visualisation analysis of Project-Based Learning (PjBL) in mathematics education, analysing 242 articles published between 1986 and 2024 from the Web of Science Core Collection and Scopus databases. Utilising CiteSpace software, the study systematically examines research hotspots, themes, and emerging trends through keyword co-occurrence, timeline visualisation, and keyword burst detection. The results indicate a potential increase in annual publications, supported by a statistical curve fitting with an R^2 value of 0.8405. The United States leads in publication volume, followed by Indonesia and Spain, while China and Australia demonstrate outstanding performance in international collaboration with the highest centrality. The study reveals that although PjBL in mathematics education has attracted considerable research interest, the formation of core author groups remains limited, with only five primary research clusters demonstrating relatively close collaboration. Additionally, ten high-frequency keywords and eleven clusters are identified. Research hotspots in PjBL in mathematics education are categorized into five primary themes: teacher education, interdisciplinary learning, competence development, learning environment, and higher education. The analysis of the temporal and spatial evolution of keywords and burst detection reveals that the top three research frontiers with the highest intensity are statistics education, linear algebra, and mathematical achievement. Furthermore, teacher education, higher education, and technology have emerged as the latest focal points for future research trends.

Keywords: project-based learning; mathematics education; bibliometrics; visualisation; CiteSpace

ABSTRAK

Kajian ini bertujuan untuk menjalankan analisis bibliometrik dan visualisasi secara komprehensif mengenai Pembelajaran Berasaskan Projek (PjBL) dalam pendidikan matematik, dengan menganalisis 242 artikel yang diterbitkan antara tahun 1986 dan 2024 dari pangkalan data Web of Science Core Collection dan Scopus. Dengan menggunakan perisian CiteSpace, kajian ini menganalisis secara sistematik fokus penyelidikan dan tema penyelidikan, serta mengenal pasti trend yang sedang berkembang melalui kata kunci, visualisasi garis masa, dan pengesanan peningkatan kata kunci. Analisis menunjukkan potensi peningkatan dalam jumlah penerbitan tahunan, disokong oleh pemadanan lengkung statistik dengan nilai R^2 sebanyak 0.8405. Amerika Syarikat mendahului dari segi jumlah penerbitan, diikuti oleh Indonesia dan Sepanyol, manakala China dan Australia menunjukkan pencapaian dalam kerjasama antarabangsa dengan pemusatan tertinggi. Kajian ini menunjukkan bahawa, walaupun PjBL dalam pendidikan matematik telah menarik minat penyelidikan yang ketara, pembentukan kumpulan penulis teras masih terhad, dengan hanya lima kelompok penyelidikan utama yang menunjukkan kerjasama yang agak rapat. Selain itu, sepuluh kata kunci berfrekuensi tinggi dan sebelas kelompok telah dikenal pasti. Fokus penyelidikan dalam PjBL dalam pendidikan matematik dikategorikan kepada lima tema utama: pendidikan guru, pembelajaran antara disiplin, pembangunan kecekapan, persekitaran pembelajaran, dan pendidikan tinggi. Analisis evolusi temporal dan spatial kata kunci serta pengesanan lonjakan menunjukkan bahawa tiga bidang penyelidikan dengan intensiti tertinggi adalah pendidikan statistik, algebra linear, dan pencapaian matematik. Selain itu, pendidikan guru, pendidikan tinggi, dan teknologi telah muncul sebagai tumpuan utama bagi trend penyelidikan masa hadapan.

Kata kunci: pembelajaran berasaskan projek; pendidikan matematik; bibliometrik; visualisasi; CiteSpace

1. Introduction

In recent years, education has been experiencing a paradigm shift from traditional teacher-centred to student-centred learning processes (Alam 2023). Compelling evidence suggests that a student-centred approach significantly influences the quality of learning by promoting active, deep, self-regulated, and collaborative engagement (Murtonen *et al.* 2024). This educational transformation necessitated the adoption of new pedagogical approaches. Project-based learning (PjBL), derived from Dewey's educational philosophy, is an instructional approach that emphasizes hands-on experience and learning by doing in the learning process (Lam *et al.* 2009). Unlike traditional teaching, which emphasizes content delivery, PjBL focuses on employing essential content and skills to solve central problems (Demir & Önal 2021). PjBL is often used as a method of guided discovery learning with the intention of promoting self-regulated, deep-level learning (Helle *et al.* 2006; Kokotsaki *et al.* 2016).

1.1. *PjBL in mathematics education*

In mathematics education, it also stands out as an effective pedagogical approach for both teaching and learning mathematics (Tarmizi & Bayat 2012). PjBL, as a student-centred form of instruction (Kokotsaki *et al.* 2016), wherein real problems and real-life practices serve as the foundation for learners to construct their knowledge and understanding (Wang *et al.* 2023). It has been proven that PjBL is particularly suitable for attaining learning objectives, notably in cultivating mathematical competencies such as problem-solving and communication skills (Yunita *et al.* 2021).

PjBL demonstrates remarkable adaptability, effectively integrating into mathematics education across elementary (Lazic *et al.* 2021; Rehman *et al.* 2023), middle (Holmes & Hwang 2016), high school (Kurtz 2019), and university levels (Ummah *et al.* 2019). Moreover, PjBL is a holistic approach, not only fostering mathematical proficiency (Cruz *et al.* 2022; Gerhana *et al.* 2017; Holmes & Hwang 2016; Lazic *et al.* 2021; Özdemir *et al.* 2015; Siswono *et al.* 2018) but also cultivating valuable higher-order skills (Kaldi *et al.* 2011; Krajcik & Shin 2014; Lazic *et al.* 2021; Rehman *et al.* 2023) that equip students for lifelong learning and success.

To understand the impact and application of PjBL in mathematics education, it is important to note that valuable reviews already exist (Cruz *et al.* 2022; Fisher *et al.* 2020; Yunita *et al.* 2021); however, they often rely on traditional methods of literature analysis, such as inductive thematic analysis or summary writing. These approaches, while informative, can be limited by the number of studies reviewed. Consequently, they may miss broader patterns or hidden connections within the existing body of research. This paper aims to address this gap through a bibliometrics study to comprehensively understand the current state of PjBL research in mathematics education, its evolution over time, and to identify future directions for the field.

1.2. *Bibliometric analysis*

Bibliometrics is the quantitative study of physical published units, bibliographic units, or their surrogates (Broadus 1987). Compared to experience-based methods, it is a comprehensive knowledge system that combining mathematics, statistics, and philology to unlock insights from large datasets of scholarly publications (Jiang *et al.* 2023). Furthermore, the analysis provides more objective results for researchers. It empowers them to delve deeper into scientific literature, uncovering valuable insights into authorship patterns, publication trends, and other key bibliographic characteristics (Huang *et al.* 2020).

Knowledge domain mapping, a multidisciplinary approach rooted in data mining and information visualisation, aims to visually represent the structure and relationships within a specific knowledge area. By creating knowledge maps, researchers can improve knowledge navigation, understanding, and discovery (Shiffrin & Börner 2004). In recent years, the knowledge domain mapping methods have been widely applied in bibliometric studies to explore disciplinary development status, research frontiers, research hotspots, and systematic reviews (Zou *et al.* 2018).

1.3. *Research questions*

Recognising the strengths of both the bibliometric methods and the visual analysis capabilities of knowledge domain mapping, this systematic review employed these approaches to investigate PjBL in mathematics education objectively, revealing the research development status and identifying the research fronts and hotspots in the domain of the study. Specifically, it addresses the following research questions:

(1) What research hotspots and themes have emerged in PjBL in mathematics education?
(2) How have these emerging research themes evolved over time?
(3) Where are the frontiers of PjBL in mathematics education?

2. Methodology

2.1. *Data analysis tool*

Bibliometrics involves the statistical analysis of scientific texts. These methods include analyses based on co-occurrence relationships, network analysis approaches, citation relationships, indicator-based approaches, and topic-based approaches (Huang *et al.* 2020). Besides the other six commonly used software in research, CiteSpace and VOSviewer are the most frequently cited bibliometric software in research articles (Tomaszewski 2023). Compared to VOSviewer, CiteSpace has more advantages in evaluative analysis of (Markscheffel & Schröter 2021; Zhang *et al.* 2024), such as network analysis, network visualisation, clustering automatic naming, timeline, ect. (Che *et al.* 2022). CiteSpace, developed by Dr. Chaomei Chen and his team in 2004 (Chen 2004), is a Java-based software designed for bibliometric analysis, with a focus on scientific metrics and data visualisation. Its primary purpose is to reveal evolving trends within various fields and to pinpoint emerging research frontiers. Capable of visualising a field's scientific knowledge spectrum through various network types, it encompasses a wide array of functions essential for scientific research (Che *et al.* 2022). This tool is especially effective for illustrating the current research landscape, tracking the evolution of themes, and forecasting future developments within a specific domain (Chen 2006). Consequently, it overcomes the limitations inherent in traditional literature reviews.

As a next-generation information visualisation tool, CiteSpace 6.3.R1 Advanced is used to generate maps of knowledge domains based on collaboration network analysis, keyword co-occurrence, keyword cluster analysis, and keyword burst detection, uncovering the hotspots, themes, and frontiers of PjBL in mathematics education. The parameters used in CiteSpace for this study are set as follows: time slicing from January 1986 to December 2024 with a one-year slice, and node type selected individually. The top 50 nodes by frequency were extracted for author, country, and keyword analyses, while other parameters remained at their default settings, except where special instructions were applied.

2.2. *Data collection*

High-quality scientific literature undergoes a rigorous review process by experts, ensuring that the results are more representative of the related research field (De Silva & Vance 2017). These high-quality literatures serve as the foundation for bibliometric studies. To establish a robust and reliable dataset for this study, data were sourced from two major databases used in educational research: the Web of Science (WoS) Core Collection and Scopus (Wei *et al.* 2023). WoS, with over 12,400 prestigious journals and articles, provides a comprehensive dataset for understanding research trends and emerging areas (Bicheng *et al.* 2023). Scopus, the largest abstract and citation database of peer-reviewed literature (Wei *et al.* 2023), further enriches the analysis. Therefore, combining sources from WoS and Scopus, the two primary databases and citation indexes, can provide a broader range of literature in terms of the related fields (Kumpulainen & Seppänen 2022).

To ensure the comprehensiveness and accuracy of the sample data, multiple search experiments were conducted using various search terms and Boolean operators in this study. After comparing literature data obtained through these different search methods, this study specifically employed the following search terms to retrieve data: " Topic" included "project-based" or "project-oriented" or "project-centred" or "PBL" or "PjBL" referencing Guo *et al.* (2020) and Lin *et al.* (2023) ; "Topic" included "math*" or "statistics" or "calculus" or "algebra" or "geometry" or "probability" or "arithmetic" referencing Cevikbas *et al.* (2024) and Yang *et al.* (2021). Then, the results are combined using the Boolean operator "AND" to narrow the search results to the subject of this study, which is project-based learning in mathematics education. Based on these search strings, the investigation was carried out in July 2024. To capture the research results as comprehensively as possible, the time span was set to include all years. This yielded a dataset of 5892 references for further analysis, with 1904 originating from WoS and 3988 from Scopus.

Due to the different data format requirements of CiteSpace for WoS and Scopus, separate data export and processing are indispensable. The search findings from WoS were exported in "plain text" format with full records, while Scopus data was exported as full records using "CSV". Since CiteSpace uses the WoS textual data format, both the WoS and Scopus data were pre-processed using the built-in CiteSpace data converter before analysis to ensure a consistent data structure.

2.3. *Data processing*

At this stage, data cleaning filters were applied based on the inclusion and exclusion criteria for the manuscripts, as follows: (1) The material type was limited to "Articles", and the language of these studies was restricted to "English". Consequently, 2935 valid literature records were initially retrieved for further analysis. (2) Papers irrelevant to PjBL in mathematics education were excluded. To ensure the representativeness and accuracy of each record, the title, keywords, and abstract of all records were carefully evaluated. For example, the abbreviation PBL refers to "problem-based learning," "planetary boundary layer," or other terms. (3) Duplicates were removed from both datasets to ensure accurate results. Since some articles are indexed by both WoS and Scopus, comparisons of titles, authors, journals, abstracts, and other information were conducted to remove any duplicate literature, thereby avoiding redundant analysis. Following these steps, a total of 242 valid literature records remained for further analysis. A flowchart summarizing the data collection, processing, and analysis stages of this study is presented in Figure 1.

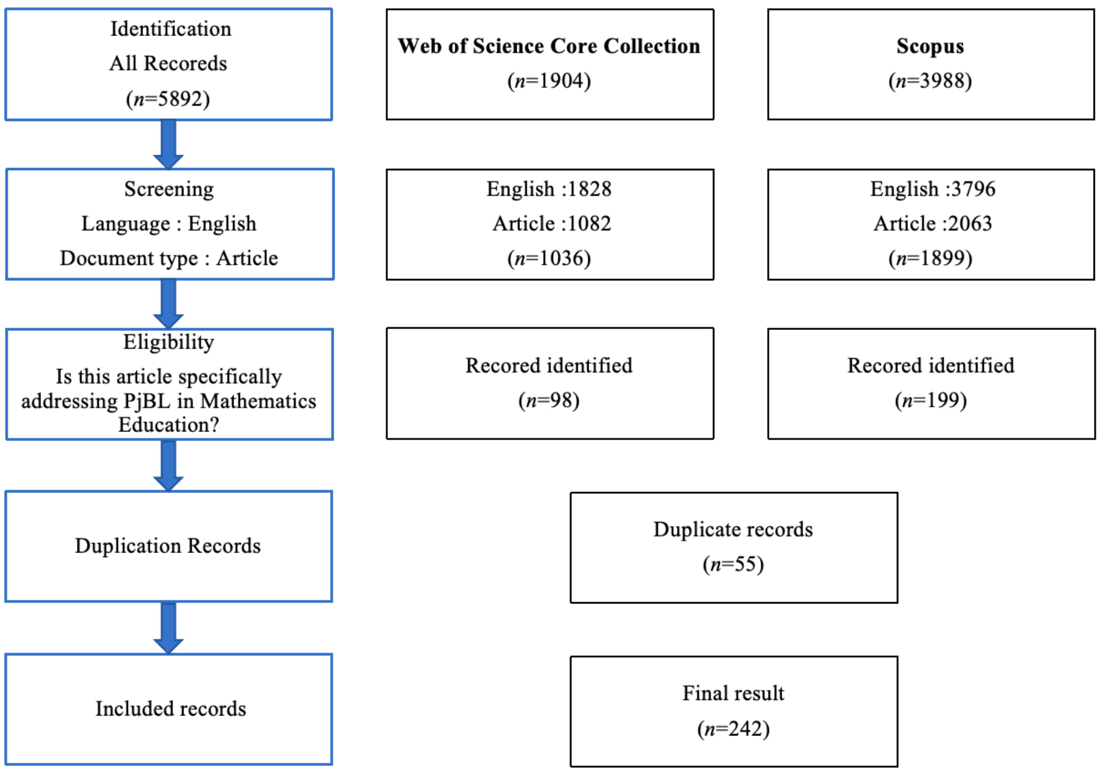

Figure 1: The flowchart of included publications in this study

3. Finding and Discussion

3.1. *Annual publication analysis*

The number of publications and citations serves as a key indicator for assessing the progress of a discipline (Wang *et al.* 2023). Creating a time distribution chart of literature quantity allows for an effective evaluation of the current research status in the field and provides insights into its developmental trends and dynamics. Figure 2 illustrates the evolution of PjBL in mathematics education from 1986 to 2024, divided into three development phases: the initial stage (1986-2005), the medium stage (2006-2018), and the rapid stage (2019-2024). From 1986 to 2005, the field experienced slow, steady growth, with fewer than three articles published annually. The medium stage, from 2006 to 2018, was characterized by a gradual increase in research output, ranging from four to ten publications per year. Finally, a significant upturn occurred in 2019, marking the beginning of a rapid growth phase where annual publication counts surpassed ten articles.

To forecast future publishing patterns, a polynomial was fitted to the number of publications, generating a fitted curve. In Figure 2, the blue line represents the yearly number of literature records, while the red dashed line shows an exponential fit based on the annual publications of PjBL research in mathematics education. The trend equation is $Y = 0.0685x^2 - 1.2901x + 6.0527$. Here, Y represents the number of publications, and x represents the publication year in chronological order. The R-squared value of the fit is 0.8405, indicating a strong positive correlation between the model and the data. The model suggests that the number of annual publications has experienced exponential growth in recent years and will continue to increase according to the trend line. According to Bicheng *et al.* (2023), a trend of exponential growth in yearly publications indicates that the field has not yet reached saturation. This suggests that research in the area continues to evolve rapidly. New theories, methods, and technologies are likely to emerge as researchers continue to explore PjBL in mathematics education. Therefore, this quantitative analysis of annual publications suggests a promising future for research on the application of PjBL in mathematics education.

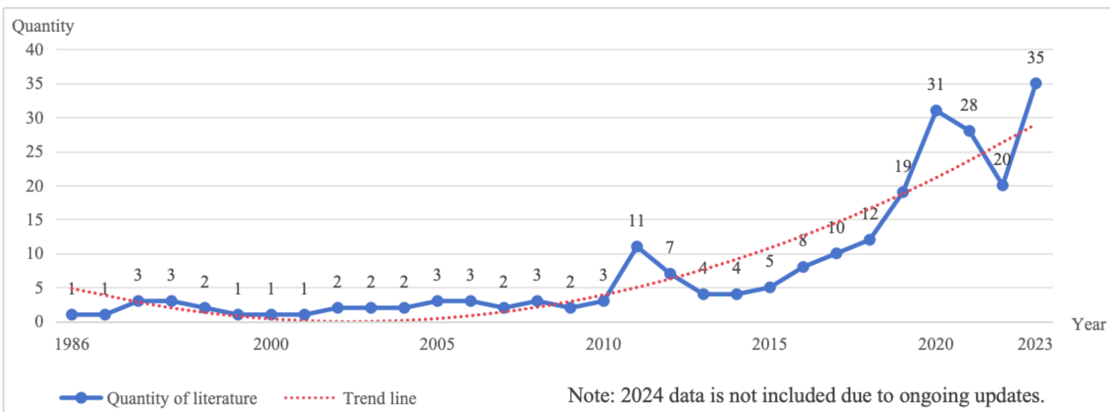

Figure 2: The number of annual publications and growth trend

3.2. *Distribution of country*

The volume of publications from a particular country or region indicates its significance, impact, and contribution to the research field (Wang *et al.* 2020). In the field of PjBL in mathematics education, 43 countries contributed to the study. Table 1 shows the number of publications, centrality, and percentage for the top ten countries, which collectively contribute 207 articles, representing 85.54% of the total publications. As shown in the table, the USA leads with 99 publications, making up 40.91% of the total, and significantly outpaces other countries. Other countries with more than ten publications include Indonesia (25), Spain (15), China (14), Turkey (13), and Mexico (12).

Analysing collaboration between countries can help identify their degree of collaboration and key influencers in the field of PjBL in mathematics education (Chen *et al.* 2022). Figure 3 presents a national collaboration network that visually displays the number of publications through node size and collaboration relationships through line width. As shown in Figure 3, there are 43 nodes and 29 connections, with a network density of 0.0321. Each node represents a country. The width of the connection line indicates the level of collaboration between countries: the thicker the line, the closer the collaboration.

Table 1: Top ten countries by number of publications

Country	Number	Centrality	Percentage
USA	99	0.13	40.91%
Indonesia	25	0.22	10.33%
Spain	15	0.21	6.20%
China	14	0.23	5.79%
Turkey	13	0	5.37%
Mexico	12	0.16	4.96%
Malaysia	9	0.21	3.72%
Australia	7	0.23	2.89%
United Kingdom	7	0	2.89%
Israel	6	0	2.48%

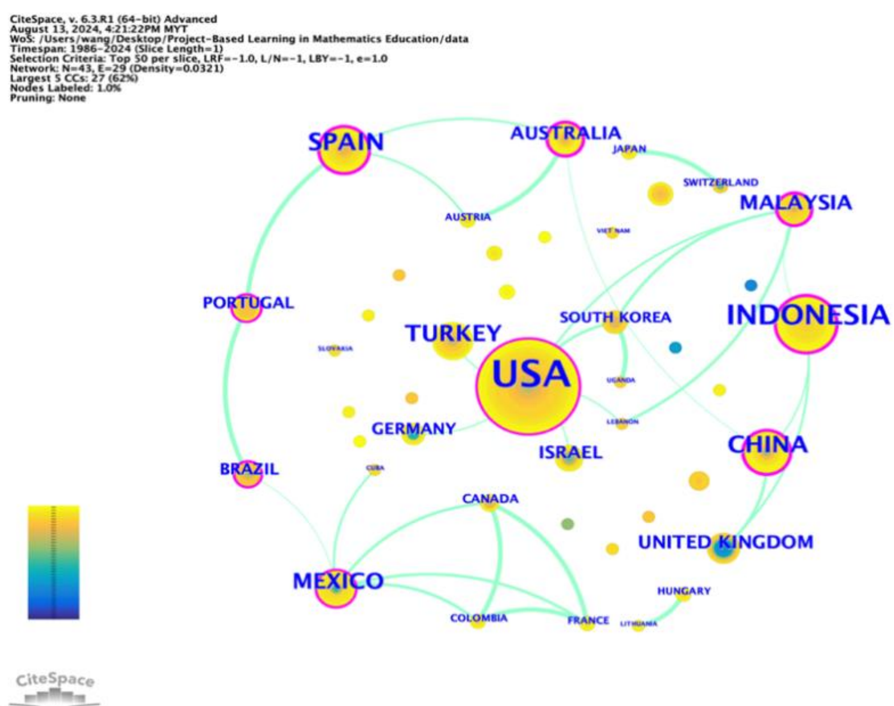

Figure 3: National collaboration network

Nodes featuring purple outer circles within the network indicate high centrality values. The centrality values of a country indicate its international influence in the field. Thus, countries such as China (centrality = 0.23) and Australia (centrality = 0.23) exhibit outstanding performance in international collaboration. Additionally, Indonesia, the USA, Malaysia, Spain, Portugal, Mexico, and Brazil have also achieved higher centrality scores, indicating that their research has received wider international attention and consequently exerts greater influence within the research field. Of particular note is that while Portugal and Brazil do not rank among the top ten in terms of publication volume, their global influence surpasses that of Turkey, the United Kingdom, and Israel, which do. This indicates that authors from Portugal and Brazil have established closer international collaborations with other authors from different countries.

3.3. *Active authors and their collaboration*

Researchers with a certain number of publications may exert a significant influence on their field. Active authors play a crucial role in driving academic development, fostering innovation, and amplifying the voice of academia. One of the primary evaluation methods for assessing active authors typically focuses on the number of publications they have produced (Wang *et al.* 2023). Price's law suggests that the number of publications is a key indicator for identifying the core authors in one field (Li *et al.* 2024). The calculation is as follows:

$$M \approx 0.749\sqrt[2]{N\max}. \quad (1)$$

The formula uses M to represent the lowest publication count qualifying an author as core and *Nmax* for the highest publication count among all authors. As presented in Table 1, *Nmax* equals three. Based on the formula, M is calculated as 1.297, indicating that authors with more than two published papers can be considered core authors. Table 2 shows 14 identified core authors who contributed 31 papers, accounting for 12.81% of all records. This represents less than 50% of the total, suggesting limited collaboration among researchers of PjBL in mathematics education.

Table 2: Ranking of core authors

Count	Author	Count	Author
3	Lou,Shi Jer	2	Han,Sunyoung
3	Capraro,Robert M	2	Gresalfi,Melissa Sommerfeld
3	Capraro,Mary Margaret	2	Dierker,Lisa C
2	Tseng,Kuo Hung	2	Diego-mantecon,Jose-Manuel
2	Shih,Ru Chu	2	Cross,Dionne
2	Marshall,Jill	2	Boaler,Jo
2	Liu,Yi Hui	2	Blanco,Teresa F

To investigate the collaborative density and connections among authors researching of PjBL in mathematics education, an author knowledge graph was created. Figure 4 illustrates the academic collaboration among these authors. Each node represents an individual author, with the size of the node proportional to the number of publications, while the connections between nodes indicate collaborative relationships. Overall, the network includes 246 authors and 292 collaborations. However, a dispersed author network with a low density of 0.0097. This suggests that while PjBL in mathematics education has attracted numerous researchers, collaborative efforts and the development of core author groups were relatively scarce. This situation may hinder the advancement of research in this area, limiting the identification and dissemination of effective practices in PjBL. Addressing these challenges could enhance collaborative efforts and foster a more integrated approach to research in mathematics education.

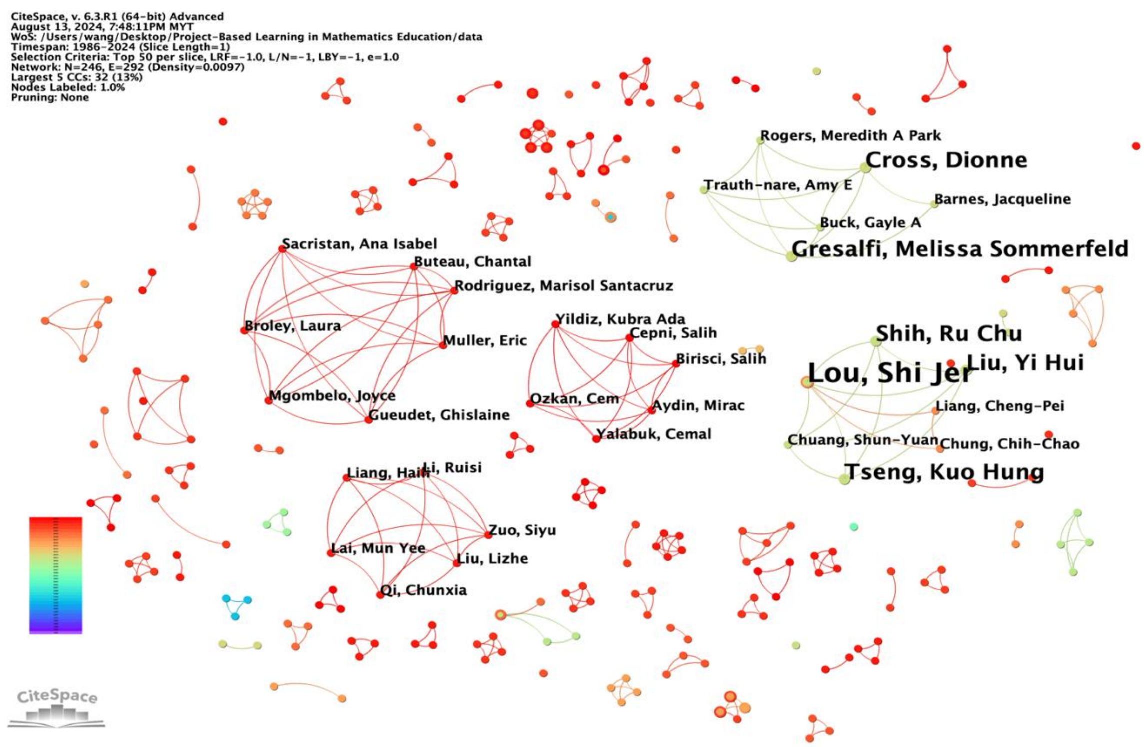

Figure 4: Authors collaboration network

Although collaboration among scholars is relatively low and limited in size, there are still five main research groups exhibiting relatively close collaboration in the field of PjBL in mathematics education. For example, researchers such as Chuang Shun-Yuan, Liu Yi-Hui, Chung Chih-Chao, Tseng Kuo-Hung, Shih Ru-Chu, and Liang Cheng-Pei have worked with Lou Shi-Jer, who may serve as a bridge between them. In conclusion, scholars researching PjBL in mathematics education demonstrate relatively weak collaborative connections, and a fully mature academic ecosystem has yet to be established.

3.4. *Research hotpots and themes*

Keywords provide a refined and concise representation of the research themes and content of a paper (Luo *et al.* 2024). Keyword co-occurrence networks can reflect core research content and hotspots of the relevant research fields (Li & Chen 2022). Using the "Keyword" module in CiteSpace, semantic repetitions were merged to generate a keyword co-occurrence network graph, which includes 530 nodes and 2351 lines. The network depicted in Figure 5 illustrates the relationships between keywords, with each node representing a specific keyword. The font size of each keyword indicates its frequency of co-occurrence. The high node centrality of certain keywords indicates their importance in PjBL mathematics education research. Notably, "project-based learning" and "mathematics education" serve as "bridges" connecting the research hotspots.

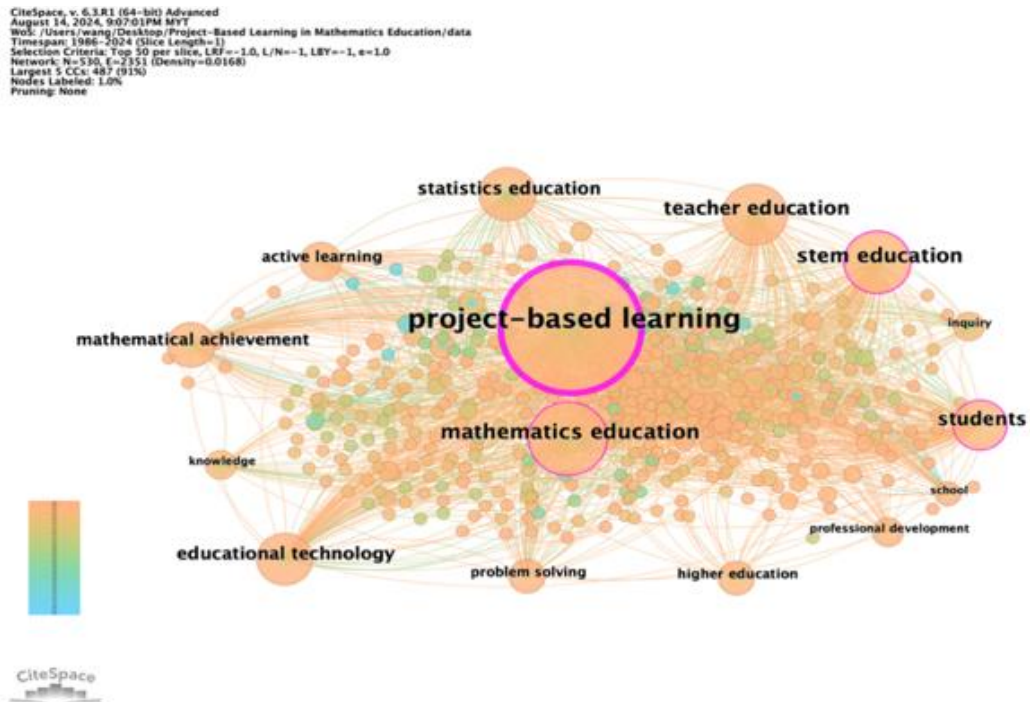

Figure 5: Keyword co-occurrence analysis

Table 3 lists the top ten keywords with the highest frequencies and centrality values. Among them, "project-based learning" and "mathematics education" had the highest frequencies, with 132 and 41 occurrences, respectively. These were followed by the keywords "STEM education", "students", "teacher education", "statistics education", "active learning", "problem solving", and others. From the analysis of the centrality, apart from "project-based learning" and "mathematics education", the keyword "students" showed the highest centrality value, followed by "STEM education", "teacher education", "statistics education", "active learning", "problem solving", and others, indicating that these keywords have been central to researchers' focus and have exerted a significant influence.

To demonstrate the interactions among keywords, keyword clustering was performed to create a keyword clustering map for analysing research themes. Keyword cluster analysis was based on the log-likelihood ratio (LLR) algorithm, as it usually provides the best results in terms of the uniqueness and coverage of topics associated with clustering (Xiao *et al.* 2017). The clustering results are presented in Figure 6, and the cluster effectiveness was evaluated using two indicators: Q-value (Modularity) and S-value (Silhouette). The Q-value is an indicator of cluster validity, with higher values indicating more effective network clustering. The Silhouette value, on the other hand, evaluates the homogeneity within the network, with greater values reflect higher uniformity. Typically, a Q-value above 0.3 indicates a well-defined network structure, and a cluster is considered reasonable when S > 0.5 and highly reliable when S > 0.7 (Li & Chen 2022). As shown in Figure 6, the values Q = 0.5793 > 0.3 and S = 0.8817 > 0.7 suggest that the clusters are well-structured and highly reliable.

Table 3: Top ten keywords with the highest frequency and centrality

No	Keywords	Frequency	Keywords	Centrality
1	project-based learning	132	project-based learning	0.99
2	mathematics education	41	mathematics education	0.19
3	STEM education	34	students	0.12
4	teacher education	33	STEM education	0.08
5	students	26	teacher education	0.13
6	statistics education	22	statistics education	0.08
7	educational technology	21	educational technology	0.07
8	mathematical achievement	16	mathematical achievement	0.04
9	active learning	13	active learning	0.03
10	problem solving	9	problem solving	0.03

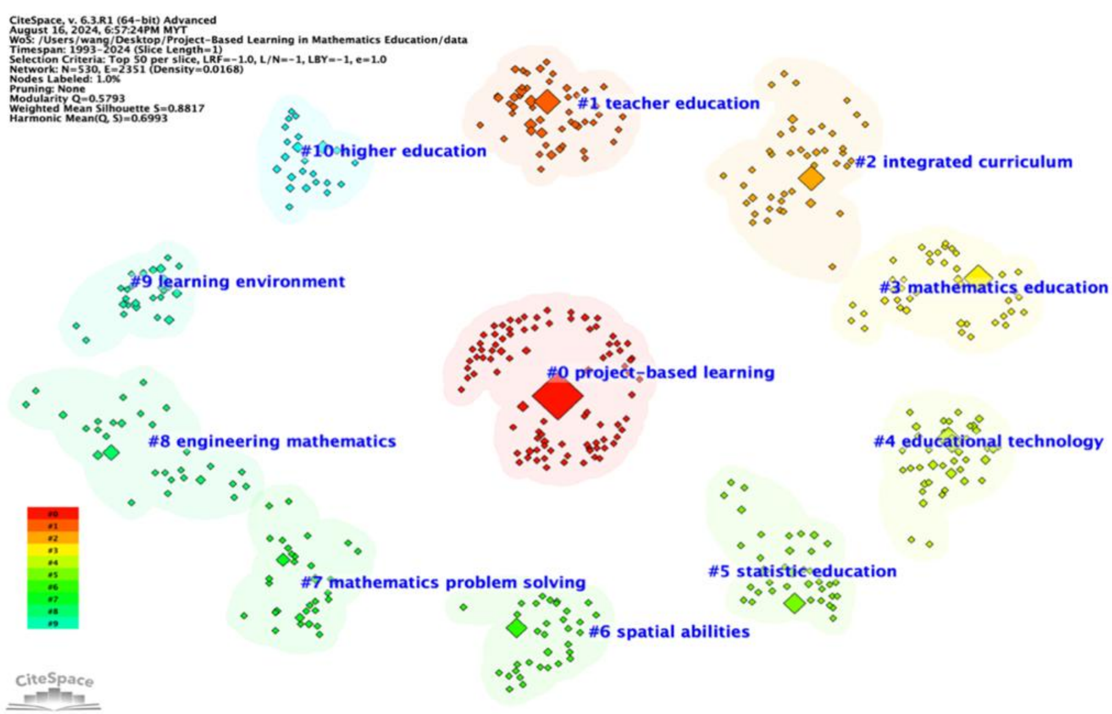

Figure 6: Clustering of co-keywords

Table 4 presents the 11 research clusters along with their corresponding information, including cluster ID, label, size, silhouette, and year. In CiteSpace, a higher silhouette value indicates greater consistency among the members of a cluster (Chen *et al.* 2022). As shown in Table 6, all clusters have silhouette values exceeding 0.82, indicating a high level of consistency among the members of the top 11 clusters, further confirming the strong clustering effect of this research and the reliability of the results.

To better identify the research themes of PjBL in mathematics education, the relevant academic literature within each cluster's alternative labels was thoroughly reviewed and analyzed. By examining the relationships between the labels of these literature topics, repetitive and similar content were combined. For example, cluster labels such as "integrated curriculum" and "engineering mathematics", which relate to cultivating mathematical achievement or using mathematics content in other disciplines to cultivate skills, were combined into two a single research theme. Similarly, since "statistics education", "spatial abilities", and "mathematics problem solving" focus on personal competence development including academic competences or other competences, they were merged into a single cluster. Additionally, "educational technology" and "learning environment" were grouped together, as using technology is one method to cultivate a better learning environment. Furthermore, given that the "project-based learning" and "mathematics education" were the primary focus of this research, they were excluded from further analysis. As a result of the cluster analysis, this study consolidates the original nine clusters into five distinct research themes: teacher education (cluster #1), interdisciplinary learning (cluster #2 and #8), competence development (cluster #5, #6, and #7), learning environment (cluster #4 and #9), and higher education (cluster #10). These themes clearly illustrate the knowledge structure and development of PjBL in mathematics education.

Table 4: Main Clusters of PjBL in mathematics education

Cluster ID	Label (LLR)	Size	Silhouette	Year
0	project-based learning	91	0.872	2019
1	teacher education	51	0.827	2017
2	integrated curriculum	44	0.831	2018
3	mathematics education	42	0.876	2021
4	educational technology	41	0.843	2014
5	statistics education	39	0.864	2008
6	spatial abilities	35	0.911	2017
7	mathematics problem solving	33	0.899	2020
8	engineering mathematics	30	0.937	2019
9	learning environment	26	0.879	2019
10	higher education	24	0.949	2018

3.4.1. *Theme 1*: *teacher education*

The theme of "teacher education" (#1) within the context of PjBL in mathematics education primarily focuses on the professional development of mathematics teachers, highlighting the critical importance of equipping educators with the competencies necessary to effectively implement PjBL. Unlike other subjects such as science, where PjBL is more established, mathematics teachers may encounter specific challenges in designing and executing PjBL lessons due to a relative lack of resources (Lee 2022). Therefore, support for teachers adopting PjBL is significant in motivating them to implement and sustain the use of PjBL (Kokotsaki *et al.* 2016). As Rogers *et al.* (2011) found, teachers' perceptions and understanding of PjBL significantly influence their classroom practices, making it crucial for professional development to provide the tools and support necessary for effective PjBL integration.

According to the records, this study categorizes research subjects of mathematics teachers into two distinct groups: pre-service and in-service teachers. For pre-service mathematics teachers, PjBL can be integrated into courses designed to prepare them for their future roles as professional educators (Retnawati *et al.* 2023). As highlighted by Montesdeoca (2023), introducing PjBL strategies during pre-service teacher training equips future educators with knowledge that can be applied to their ongoing professional development. These programmes help them learn how to design and implement engaging projects, facilitate student collaboration, and provide effective feedback.

For in-service teachers, researchers in teacher education have explored strategies to help mathematics teachers effectively utilise PjBL. For instance, researchers have focused on in-service mathematics teachers' initial experiences during their first year of implementing PjBL, including the psychological and physical barriers encountered and the strategies they employed to overcome these challenges (Rogers *et al.* 2011). Cruz *et al.* (2023) found that in-service teachers showed interest in learning and using PjBL, which can help them identify mathematical concepts that are often challenging for their students to grasp. Additionally, Qi *et al.* (2022) introduced a process in which mathematics teachers engage in Lesson Study—a job-embedded professional development initiative—to deepen their understanding of the knowledge and practices required for PjBL implementation. Furthermore, as Choi *et al.* (2019) found, teacher self-efficacy is positively influenced by the increased use of PjBL. This enhancement in self-efficacy is associated with improved class preparation, greater efforts to engage students, and more frequent student idea-sharing in the classroom. Overall, to effectively implement PjBL, teachers require a combination of both formal education and ongoing professional development.

3.4.2. *Theme 2*: *interdisciplinary learning*

PjBL is a pedagogical approach that emphasizes real-world problem-solving and interdisciplinary collaboration (Zhang & Ma 2023). It involves students tackling complex, open-ended challenges that require knowledge and skills from multiple disciplines (Drobnic Vidic 2023). Unlike traditional instruction, which focuses on individual learning from textbooks and structured questions, PjBL fosters a community of learners working together to address authentic problems (Chu *et al.* 2017). This method aims to develop future-oriented competencies in students, including creative thinking, problem-solving, critical thinking, communication, and collaboration (Zhang & Ma 2023).

Mathematics serves as a foundational discipline for many academic areas, making its integration with other subjects both natural and beneficial (Drobnic Vidic 2023). For example, Han *et al.* (2016) employed interdisciplinary PjBL over three years to examine student achievement across four mathematical topic areas. The results demonstrated that students in the interdisciplinary PjBL group outperformed those in non-PjBL groups in geometry, probability, and problem-solving. Another example involves Applied Mathematics students collaborating with peers from other majors to design stochastic models for hospital traffic using modelling and analysis of stochastic processes. The data indicate that students successfully produced integrated solutions and collaborated effectively despite their diverse backgrounds, resulting in a meaningful interdisciplinary educational experience.

Furthermore, improving course and problem design can enhance the scaffolding of interdisciplinary PjBL (MacLeod & van der Veen 2020). For example, Kuo *et al.* (2019) promoted students' learning motivation and creativity through a STEM interdisciplinary PjBL course focused on human-computer interaction system design and development. Additionally, Drăgănoiu *et al.*

(2023) introduced a multidisciplinary, game-like approach called DigiMathArt for teaching mathematics and programming. In this method, students apply geometric primitives and mathematical concepts such as addition, multiplication of natural and decimal numbers, the Pythagorean theorem, trigonometry, rotations, and first- and second-degree functions to complete their projects. This approach has proven effective in teaching a wide range of mathematical topics and programming elements.

3.4.3. *Theme 3*: *competence development*

Based on the competence development theme, a thorough analysis of the keywords and literature related to "statistic education" (#5), "spatial abilities" (#6), and "mathematics problem-solving" (#7) reveals that PjBL in mathematics education can significantly enhance personal competence, with a primarily focusing on academic achievement and non-cognitive skills. Research by Zhang and Ma (2023) revealed that PjBL significantly outperforms traditional teaching methods in improving students' academic achievement, learning attitudes, and critical thinking skills, particularly in academic achievement. Similarly, Huang *et al.* (2023) found that PjBL interventions effectively boost students' understanding and appreciation of the practical applications of statistics. Elder (2023) highlighted the role of PjBL in developing students' statistical thinking and building their confidence in reading and conducting statistical analyses of throughout the entire quantitative inquiry process. Additionally, Lopez-Chao *et al.* (2022) linked PjBL with spatial abilities, finding that PjBL initiatives significantly improved students' spatial capacity. Cruz *et al.* (2023) found that PjBL is an effective approach for cultivating mathematical structural concepts.

Beyond improving academic achievement, PjBL has also been shown to be effective in cultivating a wide range of student skills. As noted by Chu *et al.* (2017), PjBL prioritizes the cultivation of life skills, including teamwork and communication. Moreover, Wawan *et al.* (2023) found that PjBL integrated with ethnomathematics effectively improve problem-solving abilities, creative thinking, collaboration, and motivation to learn mathematics. Lee (2022) highlighted that incorporating PjBL into mathematics instruction offers a comprehensive approach to developing various intelligences and social-emotional learning skills, such as self-awareness and social awareness, positive relationships, and responsibility. Furthermore, the findings from Elder (2023) suggest that guided PjBL plays a significant role in building students' research self-efficacy, fostering their belief that they can successfully conduct research.

3.4.4. *Theme 4*: *learning environment*

The theme of "learning environment" primarily encompasses two clusters: "educational technology" (#4) and "learning environment" (#9), as depicted in the cluster diagram. Creating a stimulating and enriched learning environment involves engaging students in process-oriented learning, which significantly enhances their skills and practical experience (Cruz *et al.* 2023).

PjBL is a well-known method for creating flexible learning environments (Doppelt 2003), particularly by emphasizing authentic, real-world problem-solving (Chu *et al.* 2017; Zhang & Ma 2023). Students are often more inspired by authentic questions than by authentic contexts (Vos 2018). The hallmark of PjBL lies in its ability to connect classroom learning to real-world contexts, making the experience of learning mathematics in a PjBL classroom more engaging and motivating for students, as they can see the practical applications of mathematical concepts (Lee 2022). From the perspective of mathematics education, Vos (2018) defined authenticity as a social construct rather than a subjective perception, requiring: (1) an origin outside of the school setting, and (2) certification of originality, such as presenting physical artifacts in the classroom or receiving validation from an expert.

Technological learning environments have proven to be excellent settings for developing mathematical skills. For example, virtual environments are valuable tools for both teachers and students in distance learning-based courses, enhancing motivation and developing key skills such as mathematical visualisation, problem-solving, and logical thinking (Ruiz Loza *et al.* 2022). Additionally, numerous open digital resources, designed to be engaging and interactive, offer dynamic programmes that effectively promote general mathematics learning and practice (Hossein-Mohand *et al.* 2021). More importantly, technological learning environments are particularly well-suited for implementing key methodologies like PjBL, which is renowned for its effectiveness in enhancing mathematical competencies (Ruiz Loza *et al.* 2022). For example, Demir and Önal (2021) emphasized the benefits of integrating PjBL with technology, believing that this integration will more effectively improve both students' attitudes and academic performance. Cruz *et al.* (2023) developed an online course to explore how PjBL can enhance the understanding of mathematical structural concepts. Similarly, Drăgănoiu *et al.* (2023) designed a game-like 3D virtual environment that combines PjBL, aiming to teach mathematics concepts through practical application effectively. Overall, modern digital technology significantly enhances students' abilities across all academic levels. However, effective technology integration requires careful guidance and support to maximize its potential for creativity (Kokotsaki *et al.* 2016).

3.4.5. *Theme 5*: *higher education*

Numerous studies have explored the effectiveness of PjBL in higher education (Kokotsaki *et al.* 2016). It is widely regarded as a promising approach for improving student learning outcomes in this context (Guo *et al.* 2020). Kuo *et al.* (2019) implemented PjBL to investigate college students' learning experiences and found that it enhanced participants' overall motivation, self-efficacy, and understanding of the importance of learning for future career development. Similarly, Ruiz Loza *et al.* (2022) described the implementation of a virtual learning environment aimed at enhancing active learning courses by developing visualisation skills and mathematical competencies among undergraduate students. Additionally, PjBL has also proven beneficial for graduate students. Elder (2023) found that graduate students appreciated guided PjBL over more traditional alternatives, which motivated them to succeed in their projects, draw connections to their careers, and continue applying the skills and knowledge gained beyond the statistics course.

3.5. *Research evolution*

To analyze the historical development of clusters over time, a combined timeline visualisation network of keyword clusters was created, as depicted in Figure 7. The cluster labels are displayed on the right, and the time axis is positioned at the top. Within each cluster, keywords are arranged along the same horizontal line, with each node representing a keyword. These keywords are anchored to the year of their initial appearance and linked by lines. The timeline network facilitates observation of the duration of co-occurring keywords and the variations in specific research content within the clusters. The lines and nodes in the timeline view reveal that the research focus of PjBL in mathematics education varied across different time stages within each theme. The timeline view indicates that the research evolution of PjBL in mathematics education can be divided into three stages: prior to 2005, from 2006 to 2018, and from 2019 to the present. These three stages align with the phases of publication volume. Each theme encompasses a wide range of topics for discussion.

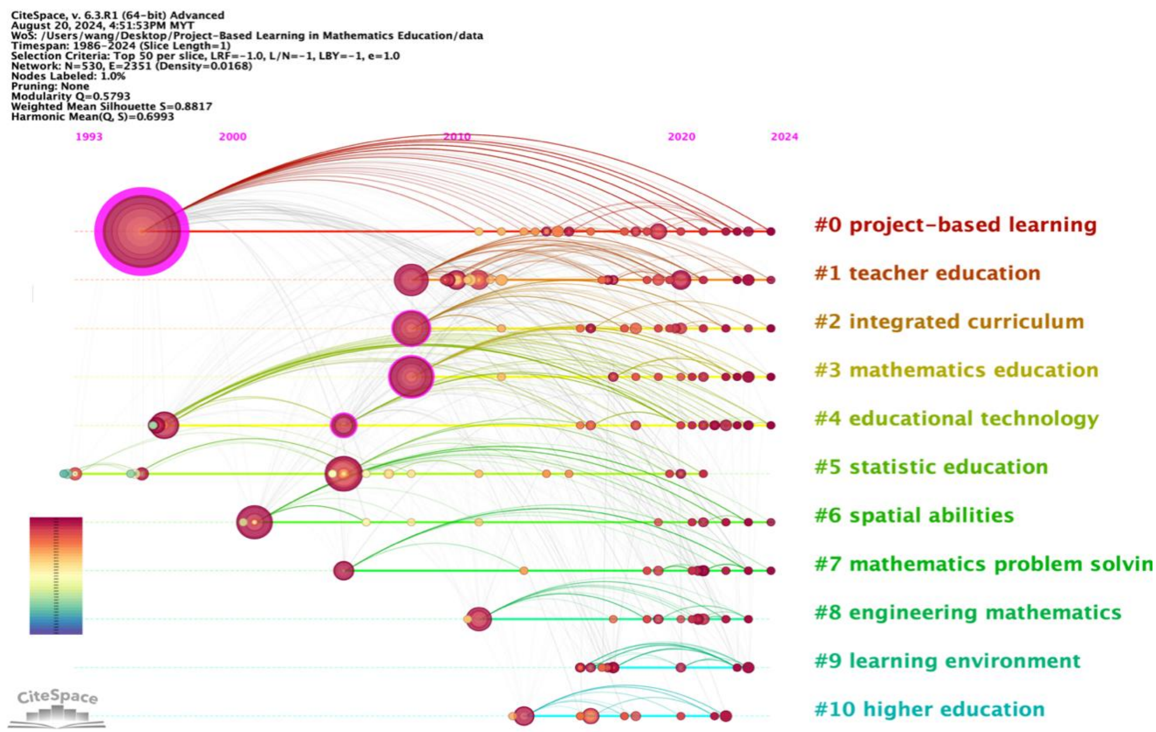

Figure 7: Timeline visualisation of keyword co-occurrence clustering analysis

Prior to 2005, the timeline view featured fewer nodes, indicating that research hotspots were relatively sparse at that time. However, some research hotspots still gained traction, such as attitudes and different learning areas using PjBL in mathematics. For instance, Hilbert *et al.* (1993) focused on calculus learning, and Leopold and Matievits (2001) paid attention to geometry learning. Additionally, Meyer *et al.* (1997) took notice of students' motivations and challenges associated with engaging in mathematics PjBL. Between 2006 and 2018, the timeline shows a relatively higher density of nodes on the timeline. However, these were concentrated in a few themes, such as teacher education, integrated curriculum, and engineering mathematics. For instance, STEM education, which connects mathematics with interdisciplinary subjects, received significant attention. This trend reflects a growing awareness of the need for pedagogical strategies that connect mathematical concepts with real-world applications. Beginning in 2019, there has been a significant rise in the number of nodes on the timeline, accompanied by a greater density within each theme. This trend suggests a diversification of research hotspots and indicates that the field is becoming more robust and multifaceted. The network analysis demonstrates positive progression in most clusters from 2019 to 2024, highlighting a shift towards a more comprehensive exploration applications of PjBL in mathematics education. These developments may guide future pedagogical practices and policy decisions, encouraging educators to adopt a wider range of strategies that utilise PjBL across various learning environments.

3.6. *Research frontiers*

The emergence of keywords over time may indicate shifts in research topics and hotspots within a field (Chen 2006), suggesting that a particular topic has either become or is gaining unusual attention from researchers during a specific period. Using the parameters γ [0,1] = 0.4 and Minimum Duration = one in CiteSpace, ten burst keywords were detected. As shown in Fig. 12, from 2010 to 2024, keywords such as "inquiry", "mathematics education", and "mathematical achievement" are identified as burst keywords. In the figure, "Year" refers to the year of the original publication, "Strength" denotes the burst intensity, and "Begin" and "End" indicate the start and end times of the burst keywords, respectively. The red line corresponds to the duration of the keyword's emergence, indicating that it received researcher attention during that period. Conversely, the blue line represents periods without significant keyword emergence.

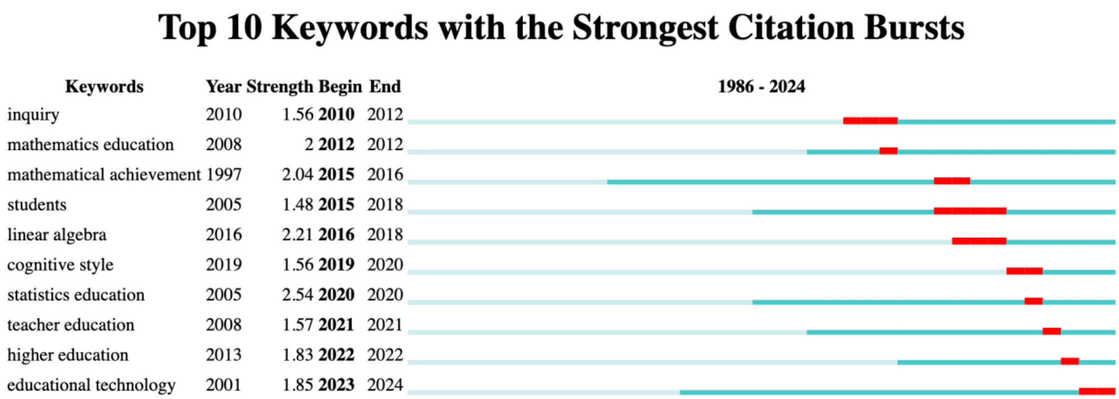

Figure 8: Top ten burst keywords

From the keyword burst detection results, higher emergence intensity indicates greater attention from the academic community. Of all the burst keywords, the top three with the highest intensity are "statistics education", "linear algebra", and "mathematical achievement", followed by "mathematics education", "educational technology", "higher education", "teacher education", "inquiry", "cognitive style", and "student". This suggests that in recent years, the use of in specific mathematics areas to cultivate students' achievement has gained attention.

Additionally, from a temporal perspective, the burst keywords can be divided into four timelines: From 2010 to 2012, "inquiry" and "mathematics education"; From 2015-2018, "mathematics achievement", "students", and "linear algebra". From 2019 to 2020, "cognitive style" and "statistics education"; From 2021 to now, "teacher education", "higher education" and "educational technology". Currently, "educational technology" has become the most recent research focus. This indicates that discussions about critical technologies related to PjBL implementation have emerged.

4. Conclusion

This study presents an overview of the outcomes from a bibliometric and visualisation analysis focused on PjBL in the context of mathematics education, utilising data from the WOS Core Collection and Scopus databases. A systematic review was conducted on 242 publications related to this field, examining the development of research themes, significant trends, and potential future directions. The primary findings of this analysis are as follows:

(1) Research on PjBL in mathematics education has undergone three distinct developmental phases: an initial stage (1986-2004), a medium stage (2005-2018), and a rapid stage (2019-2024). The exponential growth trend of this research area suggests that it is far from saturated, with new avenues of exploration and topics likely to continue emerging. Therefore, this dynamic landscape provides an opportunity for educators to engage with the latest developments and to continually refine their instructional strategies, teaching practices, and curriculum development.

(2) Research themes from 1986 to 2024 can be categorized into five themes, including teacher education, interdisciplinary learning, competence development, learning environment, and higher education. The categorization of research themes highlights critical areas and subjects for attention in the learning process of PjBL. For instance, the themes related to teacher education and interdisciplinary learning suggest that mathematics educators should collaborate with colleagues from other subjects to create integrated learning experiences and equip themselves with the skills to implement PjBL effectively. Furthermore, these themes indicate that curricula should be designed to foster such collaborations, allowing students to understand the connection of knowledge across disciplines.

(3) The identification of bursts keywords highlights the emerging frontiers of this field. Previous research hotspots have centred on “statistics education”, “linear algebra”, and “mathematical achievement”, while “educational technology” has emerged as a more recent focal point. The shift of hotspots towards “educational technology” reflects the growing recognition of digital tools in the learning processes of PjBL. Therefore, educators should strive to incorporate digital platforms as an integral part of the learning experience, not just as supplementary resources. For instance, artificial intelligence (AI) tools can be used to facilitate collaborative projects and foster engagement among students, thus preparing them for the demands of a technology-driven world. Additionally, policymakers can play a crucial role by providing resources and support for integrating such technologies into classroom practices.

This study acknowledges several limitations. Firstly, despite the availability of various bibliometric visualisation tools, only CiteSpace was utilised in this analysis. Using different software in future studies might yield more diverse or effective results. Secondly, the search query used to retrieve publications may not have encompassed all relevant works, potentially leading to the omission of significant materials. Future research should employ a broader range of keywords to enhance inclusivity. Lastly, this analysis is limited to English-language publications. To gain a more comprehensive perspective, future research should incorporate publications from additional databases, such as China National Knowledge Infrastructure (CNKI).

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