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Review article

Research hotspots and development trends of international learning cycle model:Bibliometric analysis based on CiteSpace

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ABSTRACT

The Learning Cycle Model (LCM) is an inquiry-based teaching strategy and curriculum model that has been researched and practiced for almost half a century and has achieved good educational results in science education, especially in primary and secondary schools. This study collected LCM educational research data to better understand the recent progress of LCM educational research. It used the bibliometric analysis software CiteSpace for the first time to sort out the overall development of LCM. Compared to other literature review methods, we obtained a more comprehensive picture of the current research hotspots and future research trends in LCM research. First, we searched 498 articles from the Web of Science core collection between 2000 and May 16, 2023. The trajectory of LCM research was identified by analyzing publication trends, authors, countries/regions, and research institutions. Secondly, we obtained the keyword co-occurrence map and clustering map through CiteSpace's built-in algorithm to analyze the main areas and research frontiers of this study. Meanwhile, the development trend is shown by co-keyword burst detection. After analysis, this study found that the current research hotspot findings focus on conceptual learning, validity research, and integration with different teaching processes. The research frontiers are mainly related to teacher professional development and research on the impact of LCM on learning outcomes. Finally, this study discusses future research directions, including research on the impact of LCM on 21st century skills, comparison with other modes of inquiry teaching and learning, and its use in engineering education, to promote better development of LCM.

1. Introduction

The rapid development of science and technology has brought about widespread and profound changes and impacts in all areas of social life since the second half of the 20th century. Social development has completed the transformation from industrialization to knowledge. In the wave of informationization with knowledge production and knowledge innovation as the core, educational concepts and learning methods have undergone profound changes. Today, a variety of educational models have been developed and implemented at different levels of teaching in order to transfer the increasing fund of knowledge to the students in the most effective way [1]. The theories proposed by cognitive development theorists gained significant influence within educational sciences during the 1950s, leading to widespread adoption worldwide [2]. Consequently, the primary emphasis shifted towards conducting studies designed to enhance the effectiveness of both teaching and learning processes. The competition for space research was influential in this process,

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interest in science increased and research-based learning and teaching approaches were adopted. One of the most important of these approaches is the Learning Cycle model(LCM) [3]. LCM was developed by Robert Karplus. In 1977, on the basis of the theory of mental development introduced by the famous educator and psychologist Piaget [4]. LCM were particularly important in the program which was developed by Karplus and his colleagues within the scope of the Science Improvement Study. This program is a research-based approach that centers on student-centered learning [5].

One of the most applied models of LCM is the research-based learning, also known as 5E Learning Cycle Model (5E LCM). 5E LCM was developed in 1987 by the Biological Sciences Curriculum Study (BSCS) based on constructivism. After nearly half a century of research and practice, it has achieved good pedagogical results in science education, especially in primary and secondary science education. It has gradually become the most widely used model of inquiry teaching and curriculum development [6], known as the "global standard for science curriculum development" [7]. Based on the 5E LCM, alternative models such as 3E, 4E and 7E have been developed and used at every stage of science education [8].

Numerous researchers have employed experimental research methodologies to investigate the impact of LCM on learners since its inception. These inquiries have revealed the favorable effects of LCM across multiple dimensions, including but not limited to conceptual transformations, learning dispositions, and motivational factors [9–14]. However, in these studies, it is seen that the effect size of the LCM on learners differs from study to study. This difference may stem from the differences among the variables included in the study such as the subject of the study, the size of the sampling, the school type, and the duration of the application. In this regard, to interpret the knowledge of similar studies and lead to new studies, higher level comprehensive and reliable studies are needed [15]. In recent years, several systematic reviews of LCM literature and meta-analysis of LCM-related studies have been published [13,14,16–20]. Researchers hope to answer a specific question by identifying, evaluating, and synthesizing all relevant research [21]. Candace Joswick and his colleagues believe that a more robust field of research on the LCM has emerged [16].

In summary, the development of learning theories, current social needs, and the emerging empirical research on the effectiveness of LCM all indicate the importance of LCM to teaching and learning, and it is worth considering the proposition of LCM to promote the development of the field of science education. However, some of the current research reviews on LCM use traditional literature collection methods, which makes it difficult to control the overall situation of the research entirely. Another group of researchers used system review or meta-analysis to conduct reviews, but the reviews only focused on some empirical studies on the effectiveness of LCM [13,14,16–20]. None of these studies can reveal the research dynamics of LCM research in the entire educational field or educational stage, nor can they provide a panoramic view of the international development of LCM research. Therefore, it is necessary to conduct a comprehensive and in-depth review of LCM research since the new century so that scholars can more comprehensively understand the development of LCM research in the entire world education field and put forward our analysis suggestions.

The bibliometric analysis is a quantitative method that can comprehensively explore LCM-related research on a global scale by systematically collecting, organizing, and summarizing relevant research literature, ensuring the breadth and depth of the review process [22]. Furthermore, as an objective and quantifiable research method, bibliometric methods employ machine algorithms to provide evidence. This method can minimize subjective bias while assessing research quality and reliability by analyzing indicators such as changes in subject areas, citation status, author influence, literature influence, publication age [23]. Therefore, to comprehensively understand the LCM research field, we conducted a systematic analysis using scientific measurement analysis methods.

The research questions addressed in this paper are.

(1) What is the primary distribution of LCM research, and who are the principal contributing authors, countries, and institutions? What are the characteristics of their distribution?
(2) What are the hot directions of LCM research?
(3) What are the future trends of LCM research?

2. Core concepts

Science educators aspire to enhance student engagement in the classroom and elevate the role of teachers by implementing more effective pedagogical strategies. For many years, researchers in science education have grappled with the development of student-centered instructional approaches [24]. One avenue to cultivate student-centered lessons is utilizing the LCM, which empowers educators to integrate instruction into a spectrum of planning strategies.

All iterations of LCM proposed in the academic literature stem from the constructivist learning theory, which posits that students construct their own knowledge actively. LCM equips instructors to design meaningful activities that promote students' critical thinking skills [25]. By employing the LCM, students can acquire a deep understanding of scientific concepts, rectify misconceptions, delve into concepts comprehensively, and apply their learning to real-life scenarios [26]. Applying the constructivist LCM in science education enriches course content, captures students' attention, fosters enduring comprehension, challenges preconceived notions about science, and renders the course more engaging and productive [27].

Various iterations of the LCM have emerged in scholarly literature, including the 3E LCM [28], the 5E LCM [29], and the 7E LCM [8]. More recently, the 9E LCM has been proposed [30]. Each "E" in the LCM corresponds to an English word, signifying a distinct stage of the learning process [31]. Starting with the 3E LCM, each iteration expands upon the preceding one. This section introduces the three most pivotal LCM models, as they serve as crucial references for subsequent literature review in this study.

2.1. 3E learning cycle model (3E LCM)

In the 1960s, with the reform of the primary science curriculum, American academic Robert Karplus led the SCIS project and developed the SCIS curriculum. At the same time, he found considerable differences in the ability of students to learn science, understand scientific concepts, conduct investigations, or solve specific problems [28]. In 1967, Robert Karplus's team initially proposed the 3E LCM, also known as the Atkin-Karplus Learning Cycle Model, which suggested that students should discover scientific concepts through guided inquiry [32] and that teachers should summarize and introduce scientific concepts to facilitate knowledge construction. The 3E LCM is a three-stage learning-centered, activity-centered inquiry teaching and learning model based on a constructivist pedagogy. The model draws on and applies Piaget's epistemology of occurrence, dividing the teaching process into three stages: initial exploration, term introduction, and concept application.

Exploration: This stage is a student-centered exploration activity. In this process, students learn and explore new concepts through their discoveries and responses based on their own experiences of the environment. As they engage in exploration, students should begin to ask questions that their current knowledge cannot answer [28].

Term introduction: In this stage, the teacher leads this phase, guiding students to discuss the inquiry results [28]. Students build on their direct experience from the previous stage to generate concepts, derive principles and extend their reasoning skills.

Concept application: This is a student-centered stage of application and extension of knowledge in which students use the scientific concepts they have just acquired in the previous stage to solve problems in new contexts, thus verifying, applying, consolidating, and improving new concepts. Teachers can use this stage to meet with students individually to identify and address misconceptions and to help resolve them [28].

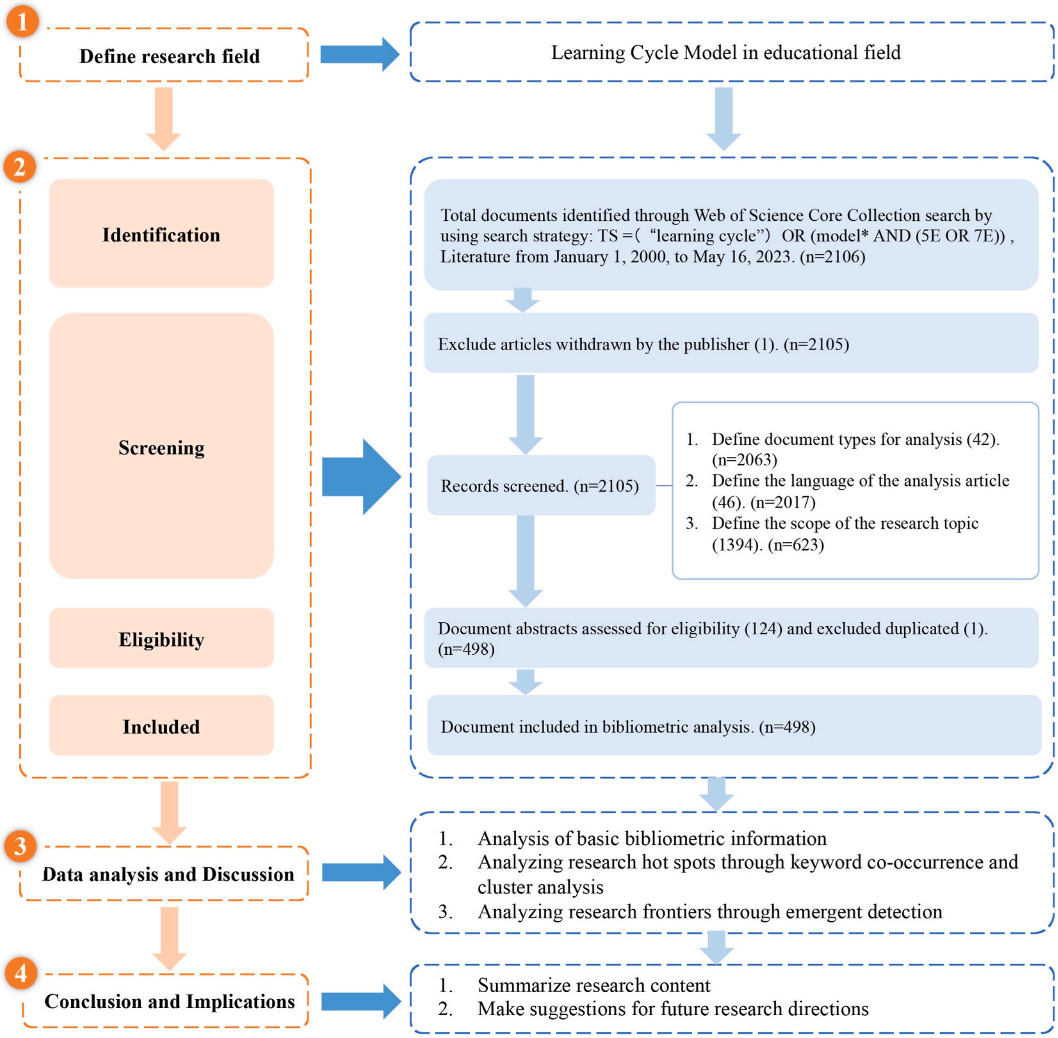

Fig. 1. Flow diagram of PRISMA methodology and bibliometric analysis.

2.2. 5E learning cycle model (5E LCM)

5E LCM is one of the teaching models developed based on constructivist and conceptual shift theories. In 1989, the Biological Sciences Curriculum Study (BSCS) team led by Rodger Bybee expanded the 3E LCM to divide the science teaching and learning process into five closely linked stages: Engage, Explore, Explain, Elaborate, and Evaluate [27]. Each stage has a specific function that contributes to the teacher's teaching consistency and helps students better understand technological knowledge, attitudes, and skills [33]. In the introduction stage, the teacher engages the students' attention and interest and activates their prior knowledge. The inquiry stage is the centerpiece of 5E LCM, where the teacher takes full advantage of the cognitive conflicts that arise during the "introduction" stage to guide and help students conduct inquiry activities into specific content to resolve any misconceptions from the previous stage. Once the inquiry is complete, the teacher guides students through the Explanation stage to correctly understand and describe key aspects of the material.

In contrast, the Elaboration stage allows students to use the new concepts gained to try to solve problems or explain new phenomena to extend and enrich the content of the previous stages. In the final stage, students are assessed and receive feedback on their learning. "Introduction" and "Evaluation" are the two new components, while "Inquiry," "Explanation," and "Refinement" correspond to Initial "Exploration," Concept Introduction," and "Concept Application." The substance is the same.

2.3. 7E learning cycle model (7E LCM)

Through years of practice and application, the American educator Eisenkraft has developed the 5E LCM into the 7E LCM with its emphasis on transfer learning, which expands "Engage" into "Elicit" and "Engage", with the Elicit phase serving as a starting point where exposing students' pre-concepts through new learning situations created by the teacher or through meaningful learning activities. Afterward, an introduction session will link the previous concepts with the new content. The following three stages are mainly consistent with the 5E LCM, except that a new "Extend" stage [8] is added at the end, which is designed to reflect, explore, find, and explain examples of applications of the concepts learned [10]. The 7E LCM makes the 5E LCM more tangible and evidence-based in its operation in teaching and learning; It stimulates students to recall the topics they have been exposed to, trains them to learn to find concepts through experimentation, and provides them with opportunities to show examples of applications of the concepts they have learned [34].

3. Methods

The research process is outlined in Fig. 1. The details of the data sources, search criteria, and methods of analysis will be presented in the following parts of this section.

3.1. Software and tools used in the analysis

The Web of Science Core Collection (WoSCC) was chosen as the study's data source. WOSCC is recognized by scholars as an excellent database for bibliometrocs. Many academics regard WoSCC as a high-quality digital literary resource database, and it is regarded as the best database for bibliometric analysis [35].

In this study, the primary tools for data statistics and analysis were the application software CiteSpace (6.2.R2). This software, developed and designed by Professor Chen Chaomei of Drexel University in the United States, is a multi-dimensional, time-sharing, dynamic information visualization tool. CiteSpace predominantly relies on co-citation analysis theory and path-finding network algorithms to assess documents and collections within specific fields [36]. It aims to elucidate critical pathways in the evolution of subject domains and the identification of knowledge turning points, often represented by key papers. Through a series of visualizations, it facilitates the exploration of potential dynamic mechanisms governing subject evolution and the identification of the frontiers in subject development [36]. CiteSpace proves particularly well-suited for assessing research status, theme evolution, and forecasting prospects within fields. The choice of CiteSpace as the primary analysis tool for this study was motivated by its comprehensiveness, analytical consistency, and user-friendliness, distinguishing it from other scientific measurement analysis software like VOSviewer and Bibiliometrix [37].

3.2. Data exploration and plan

This study follows the PRISMA framework [38], see Fig. 1 for the second stage (please note that the authors only followed the steps in scrutiny and do not conduct systematic literature review as per PRISMA methodology).

The data was retrieved from the WoSCC on May 16, 2023. The search was conducted using an advanced search. The initial search revealed the keyword types "5E learning model", "5E instruction model", and "5E model"; therefore, to ensure the completeness of the collection, a search strategy of TS = ("learning cycle") OR (model* AND (5E OR 7E)) was used. The search period was from January 1, 2000 to May 16, 2023. The search yielded 2106 records. The publisher withdrew one of the articles, and after deletion, the literature count was 2105 records. To ensure data accuracy, the following steps were undertaken.

(1) Literature type filtering: Articles, review articles, and proceeding papers were selected due to their peer-reviewed nature, academic credibility, and suitability for in-depth research and analysis within a specific field.

(2) Language selection: English was chosen as the primary language for the literature. CiteSpace assumes linguistic consistency within a dataset, and cross-language co-citation and association analysis can become complex with multiple languages. Furthermore, English is a common language for international academic discourse, facilitating comparability across different studies and enhancing the meaningfulness of literature analysis.
(3) Research scope determination: The study's scope was defined within educational research and educational research disciplines.
(4) Literature abstract review: The research team carefully examined the literature abstracts and excluded content not aligned with the study's research topic.
(5) Duplicate elimination: Duplicates were identified and removed using CiteSpace.

3.3. Data analysis

The selected 498 documents were imported into CiteSpace, with Time Slicing set to "January 2000–May 2023″, Years Per Slice set to 1 year, a cropping method of "PathFinder" and the rest of the options set by default in the software. The CiteSpace data map presents the relationship between the information in a document by forming nodes and lines; N indicates the number of nodes, and E is the number of lines. The size of the nodes reflects the frequency of references or occurrences of the data in question, and the lines indicate the relationship between the nodes. To comprehensively analyze the current situation and development trend of LCM-related research based on the characteristics of CiteSpace, this study mainly analyses its path from the following three aspects.

(1) Analysis of basic information of LCM research. The time, country, author, and institution of published literature are analyzed to understand the overview of published literature in LCM research.
(2) Analysis of LCM research hotspots. Frequency analysis, intermediary centrality analysis, and cluster analysis of keywords are conducted to construct a knowledge map and summarize the current research status of LCM research areas.
(3) Analysis of LCM research frontiers and trends. The CiteSpace burst detection method was used to identify burst keywords. Burst refers to the intensity of the sudden appearance or disappearance of keywords for a research topic in a specific research field within a certain period, which to a certain extent, represents the direction of a shift in a research trend [39]. By analyzing keyword burst detection, the famous research themes, and research trends of LCM research in different periods can be inferred.

4. Results

4.1. Analysis of basic information on LCM

4.1.1. Annual distribution of publications

Counting the number of academic papers or academic journals in a field and analyzing them provides insight into the development of the field. The literature volume shows the changing trends in academic interest in research topics over a specific time frame [40]. Fig. 2 illustrates the change in the volume of literature published.

According to the changes in the number of published papers, there are three stages of development: the nascent stage, the slow development stage, and the rapid development stage. In the first stage (2000–2005), the newborn stage, research started, and the number of published papers was relatively small, averaging one paper per year. In the second phase (2006–2013), the slow development phase, the research was slow to develop, but the number of publications increased significantly compared to the previous phase. The third stage (2013–2023) is a rapid development stage, with LCM education and teaching research developing rapidly, with publications above 30 per year, peaking at 49 in 2021. The increase in the number of documents can be attributed to various factors, including widespread access to the Internet, an increase in the number of researchers, and an expansion in the number of journals. However, by carefully reviewing the literature content of this period, we can find that the research results of this stage are more prosperous and in-depth. This reflects the increasing attention of academic circles to LCM research, and it is expected that the number of publications in this field will continue to grow in the next few years, providing more valuable insights and contributions to LCM

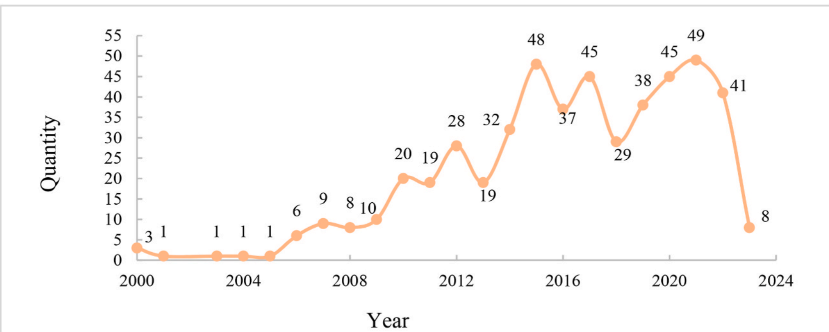

Fig. 2. Annual distribution of the number of articles issued.

education and teaching research.

4.1.2. Distribution of country/region

Focusing on the author's country or region can measure the country or region's performance in terms of research output and reflect the regional distribution of research output [37]. To understand the distribution of LCM research articles by country of origin, we obtained a network map based on the author's country/region through CiteSpace (Fig. 3).

The mapping shows 62 nodes and 49 connecting lines linking these nodes. A node represents a country/region, and the node's size indicates the number of articles published in that country/region. When two countries/regions have a collaborative relationship, a line will form, and the thickness of the line reflects how closely the countries/regions collaborate [41]. The graph's number of nodes and lines reveals the academic collaboration links between countries/regions of LCM research (density = 0.0259). Table 1 shows the top 10 countries/regions with the most published papers. The USA is in the first place regarding the number of papers published and intermediary centrality, reflecting the international influence of the USA as the origin of LCM research.

It is also worth noting that Turkey, although not as numerous as the US, is almost twice as numerous as Indonesia in third place. This underscores Turkey's substantial involvement in scientific research, which can be attributed to several factors. On one hand, education stands as a paramount determinant of economic, social, and political development [42]. Since the establishment of the Republic in 1923, the Turkish government has implemented numerous educational reforms and consistently increased investments in the education sector. Turkish citizens, in general, recognize the pivotal role of education in the nation's long-term development [43]. On the other hand, examining the historical trajectory of Turkish education reform reveals the influence of the Western education reform movement, particularly in the curriculum [44]. In the 1960s, the shortcomings of the science curriculum reform initiative led science educators to realize the limitations of traditional teaching methods, catalyzing the emergence of constructivist perspectives. Constructivists advocate that children construct their concepts through interactions with their physical and social environments [45]. Consequently, they design curricula to encourage student engagement in scientific activities, fostering better comprehension and learning [46]. This constructivist approach gained international acclaim. However, the underperformance of Turkish students in international assessments raised concerns within the Turkish Ministry of Education. In response, in 2005, the Turkish government initiated a curriculum reform plan, recognizing constructivism as a foundational learning theory and teaching strategy [47]. They supported educators in implementing constructivism in science courses, introducing the LCM as a constructivist-based tool within Turkish science education.

4.1.3. Active authors and their collaboration in LCM research

Analyzing the relationship between document authors and the number of published documents can help identify highly productive authors and assess the status of community formation [48]. Authors were analyzed visually in CiteSpace, with nodes being author names, their size representing the number of publications, label text size representing centrality, and connecting lines between nodes indicating author collaborations [49]. Fig. 4 shows the academic collaborations between authors working on LCM, with Nodes = 379,

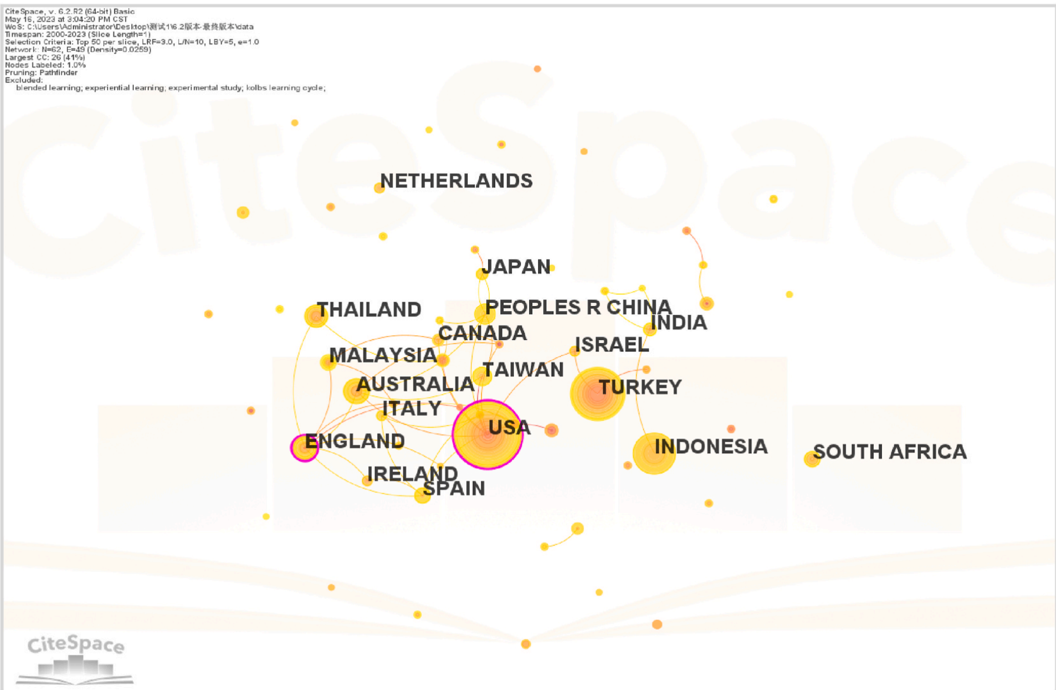

Fig. 3. Visual mapping of publications by country/region.

Table 1
Top 10 countries in terms of number of articles issued.

Number	Country/Region	Number of publications	Centrality	Mean year	Proportion(%)
1	USA	134	0.16	2000	26.91 %
2	TURKEY	87	0.03	2006	17.47 %
3	INDONESIA	46	0	2016	9.24 %
4	TAIWAN	28	0	2005	5.62 %
5	CHINA	27	0.06	2008	5.42 %
6	AUSTRALIA	19	0.06	2014	3.82 %
7	ENGLAND	17	0.11	2006	3.41 %
8	THAILAND	17	0.01	2011	3.41 %
9	SOUTH AFRICA	10	0	2011	2.01 %
10	SPAIN	9	0.03	2011	1.81 %

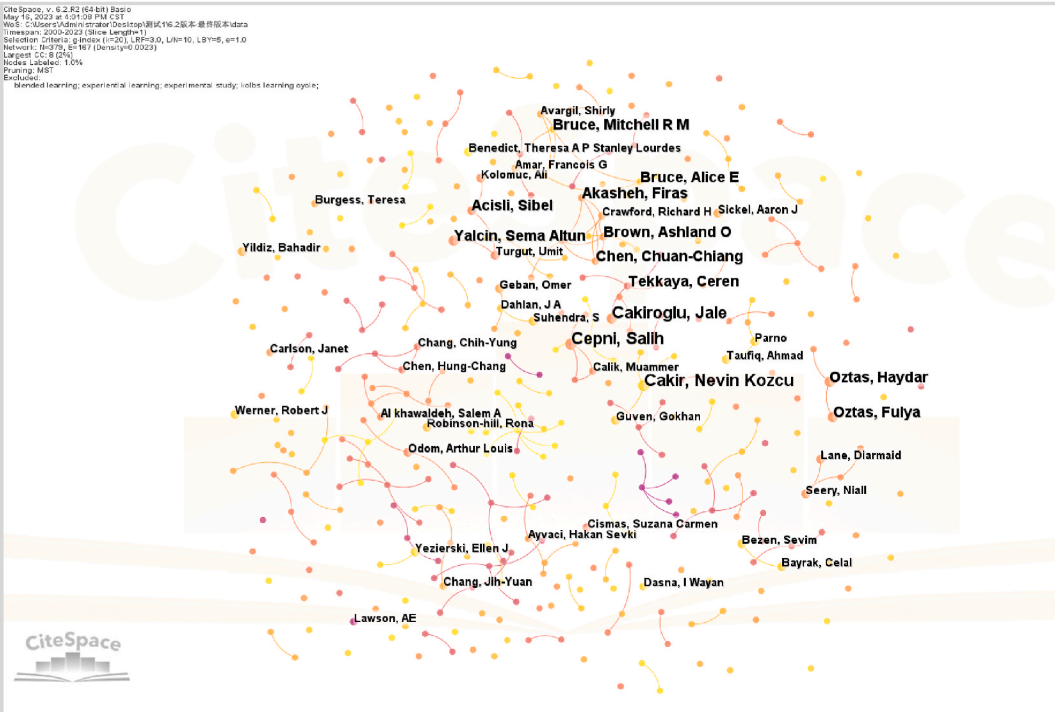

Fig. 4. Visual mapping of author collaborations in LCM research.

representing a total of 379 authors in the field, including co-authors; 167 lines, representing 163 author collaborations in the field. Density represents the density of the network, which means the "actual number of relationships" in the network divided by the "theoretical maximum number of relationships," so in general, the higher the density, the more cooperative it is [22]. The mapping network density is only 0.0023, indicating a low level of collaboration between researchers, driven mainly by "a predominantly

Table 2
Top 10 most prolific authors in the field of LCM.

Number	Author	Number of Publications
1	Cepni Salih	4
2	Cakir Nevin Kozcu	4
3	Cakiroglu Jale	4
4	Chen Chuan-Chiang	3
5	Oztas Haydar	3
6	Acisli Sibel	3
7	Bruce Mitchell R M	3
8	Akasheh Firas	3
9	Yalcin Sema Altun	3
10	Oztas Fulya	3

teacher-student academic relationship." While this helps preserve academic traditions, it is not conducive to the exchange of new ideas. In addition, there are many isolated points outside the local network, mainly due to the low number of researchers' publications and the need for high visibility. Therefore, we must establish diversified cooperative relationships and strengthen in-depth cooperation with researchers in different fields.

According to Price's law, core authors' minimum number of publications is $M \approx 0.749 \times \sqrt{N_{max}}$, where M refers to the number of papers, and N_{max} is the number of papers published by the most prolific author in the statistical year; this means that when the number of papers published by an author is greater than M, that author is a core author in the field; when the total number of papers published by core authors reaches 50 % of all papers, the field forms a core group of authors [50]. As shown in Table 2, N_{max} is 4, which when taken into the equation gives $M \sim 1.498$, meaning that authors with more than two publications are core authors in the field. The analysis of the sample literature shows that 46 scholars published two or more papers between 2000 and 2023, with a total of 108 publications, accounting for 21.69 % of the sample literature (498 papers), which is less than 50 %, indicating that there is still a need to cultivate further a core group of authors who steadily conduct continuous research. There is more room to improve the size and academic guidance of the core authors. Among them, Çepni Salih, Cakir Nevin Kozcu, and Cakiroglu Jale are the most published authors, with four articles each indicating that these scholars are at the core of the field and have more significant academic influence.

4.1.4. Distribution of institution

The number of papers published by a research institution reflects the institution's research capacity to a certain extent, and statistical analysis of the number of papers published by research institutions better reflects the development history and research results of each research institution [23]. We used CiteSpace to further analyze research institutions and their cooperative relationships in the field of LCM and obtained an institutional cooperation network map (Fig. 5). Fig. 5 shows that the connections between institutions could be more robust, indicating a low level of institutional collaboration in this research field. Table 3 lists the top 10 institutions contributing the most papers. Among the top 10 institutions that contributed the most papers, only one is a research institution (RULK-Research Libraries UK), and the rest are institutions of higher learning, which highlights the importance of higher education institutions in LCM research.

Regarding the number of published papers, institutions from Turkey hold the foremost positions, occupying four slots. This trend aligns with our previous analysis and underscores Turkey's significant emphasis on the LCM in science education. The figure also reveals the formation of a relatively centralized cooperation network centered around the California State University System (CSU). This is attributed to CSU being the most extensive four-year higher education system in the United States, comprising 25 independent colleges, including San Francisco State University, San Jose State University, and California State University, Los Angeles [51]. Consequently, the surrounding nodes primarily consist of its branch campuses.

A more detailed exploration of collaboration networks can provide researchers with a clearer insight into the research priorities of institutions at the forefront of LCM education research. For instance, an analysis of the collaboration networks centered around CSU

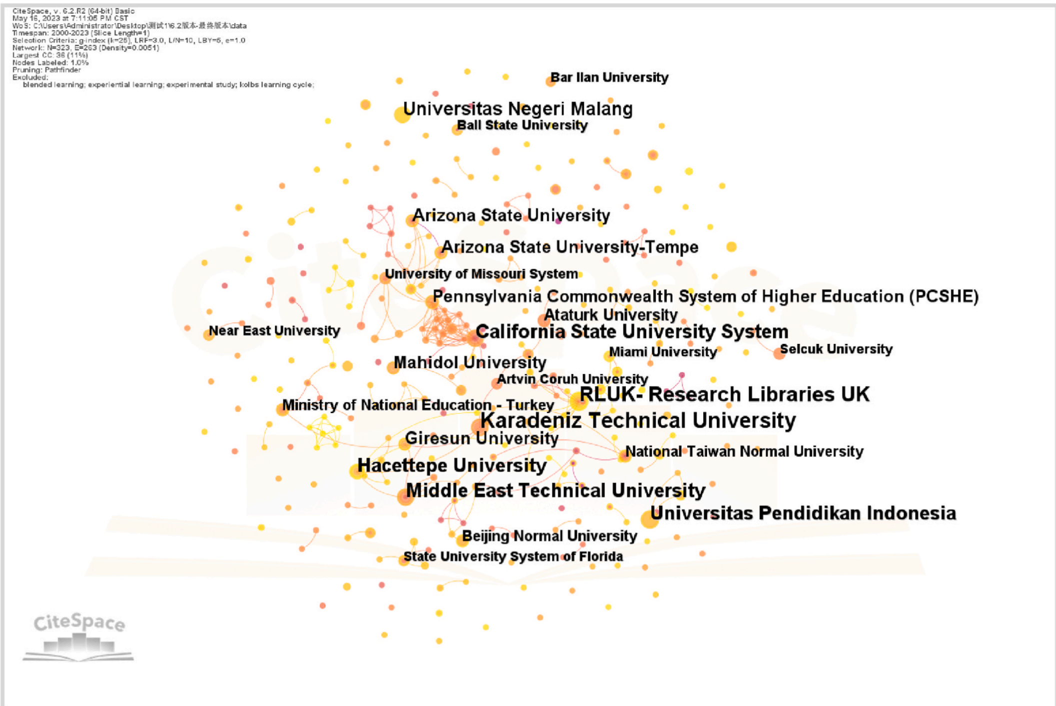

Fig. 5. Visual result of the productive with their collaborative links.

Table 3
Top 10 institutions for publications in the field of LCM.

Number	Institution	Number of Publications	Country
1	Karadeniz Technical University	13	Turkey
2	RLUK- Research Libraries UK	11	England
3	California State University System	10	USA
4	Universitas Pendidikan Indonesia	10	Indonesia
5	Middle East Technical University	10	Turkey
6	Hacettepe University	9	Turkey
7	Universitas Negeri Malang	8	Indonesia
8	Mahidol University	7	Thailand
9	Giresun University	7	Turkey
10	Arizona State University	7	USA

demonstrates a robust research interest that integrates LCM with other teaching models. These analytical findings facilitate a profound understanding of the research directions and collaborative dynamics among research institutions within the realm of LCM.

4.2. LCM research hotspots analysis

The data was imported into CiteSpace, and the node type was set to Keywords to obtain a keyword co-occurrence map (Fig. 6). The nodes represent keywords, and the size of the nodes indicates the frequency of keyword occurrences; the lines indicate the relationship between keywords, and the thickness of the lines indicates the frequency of keyword co-occurrence [22]. Fig. 6 shows 377 nodes and 911 links, with a density of 0.0129, indicating a wide range of research topics related to LCM and close links between topics. However, the overall density of the network leaves much room for improvement, suggesting that research in this area needs to be further expanded and deepened.

The keywords "5e learning cycle," "learning cycle," "science," and "education" correspond to larger nodes and are closely linked, which may reflect the common focus of researchers in the field. CiteSpace uses frequency and mediated centrality as quantitative indicators of the importance of keywords; the higher the frequency and intermediary centrality, the more critical [52]. Table 4 shows the top 10 ranked keywords for frequency and mediated centrality. We can compare the left and right sides of Table 4; there is a significant overlap between high-frequency and high intermediary centrality keywords. "5e learning cycle," "learning cycle," "science," "education," "students," "achievement," "knowledge," "conceptual science," "education," "students," "achievement," "knowledge," "conceptual change," and "science education" are the nine keywords with high frequency and centrality, indicating that scholars in the field of LCM research mainly focus on these keywords. "5e learning cycle" appears most frequently and has high centrality, indicating

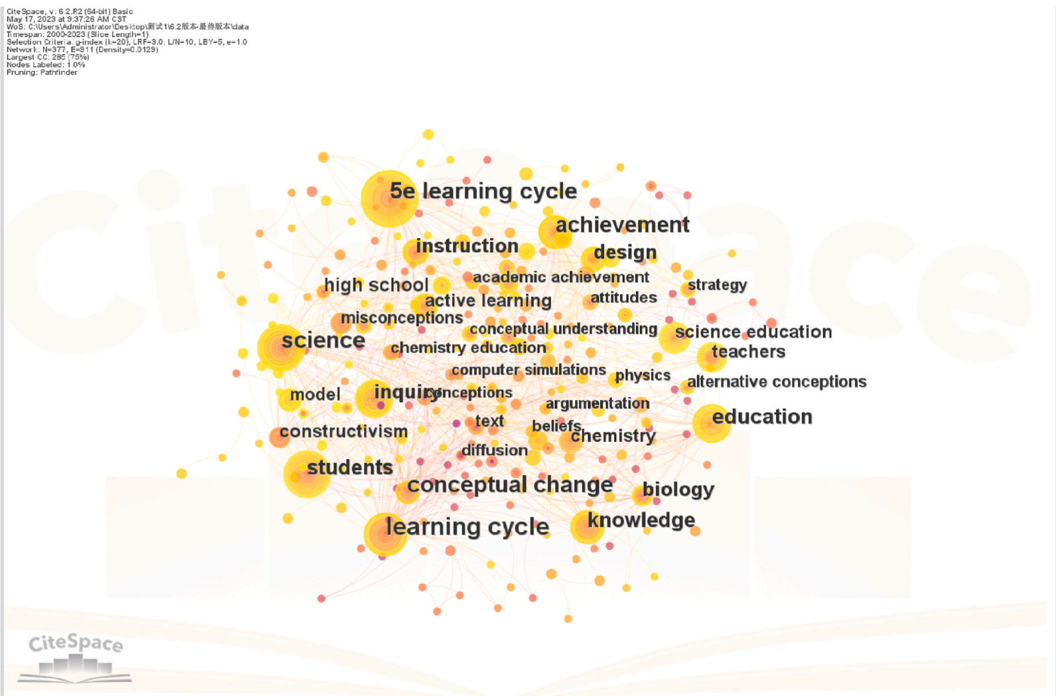

Fig. 6. Keyword co-occurrence analysis.

Table 4
Top 10 keywords in terms of frequency and centrality.

Number	Keyword	Frequency	Keyword	Centrality
1	**5e learning cycle**	82	**learning cycle**	0.27
2	**learning cycle**	53	**5e learning cycle**	0.26
3	**science**	51	**students**	0.15
4	**education**	43	**education**	0.14
5	**students**	36	**science**	0.13
6	inquiry	29	**achievement**	0.1
7	**achievement**	26	**knowledge**	0.1
8	**knowledge**	24	**conceptual change**	0.1
9	**conceptual change**	17	**science education**	0.08
10	**science education**	16	design	0.08

that current research on LCM mainly focuses on 5E LCM. "Science," "education," and "students" are the four keywords with high centrality, indicating that current research on LCM mainly focuses on 5E LCM; the high frequency and mediating centrality of the three keywords education and students suggest that they play a "bridging" role in LCM research.

In addition, the top rankings of achievement, knowledge, and conceptual change reflect the effectiveness of LCM on conceptual change and academic achievement. Analyzing the critical literature reveals that 5E LCM achieves improved learning outcomes precisely by facilitating students' conceptual change. Conceptual change often involves students' investigation and change of prior concepts that are deeply ingrained and difficult to change through traditional teaching methods [53]. There is a broad consensus among educational researchers that to facilitate conceptual change; individuals should not be seen as passive recipients of information in the teaching and learning process but rather as active learners who construct their knowledge. In other words, for a conceptual change to occur, students need to engage in active learning [54]. In science education, LCM has been shown to help teachers transform traditional teaching methods into more active educational methods. Taking 5E LCM as an example, teachers use the links "Engage" and "Explore" to allow students to expose their original knowledge in specific situations and obtain new results through exploration activities, thereby creating cognitive conflicts. In the "Explain" stage, teachers guide students to use new concepts to explain phenomena to demonstrate the understandability and rationality of the new concepts. In the "Elaborate" stage, students need to apply new concepts or methods to explain other phenomena so that the new concepts or methods can be internalized into their cognitive structures and then construct scientific concepts.

4.3. Keyword cluster analysis

The co-occurrence analysis of keywords only shows part of the current research hotspot because it does not indicate the interaction

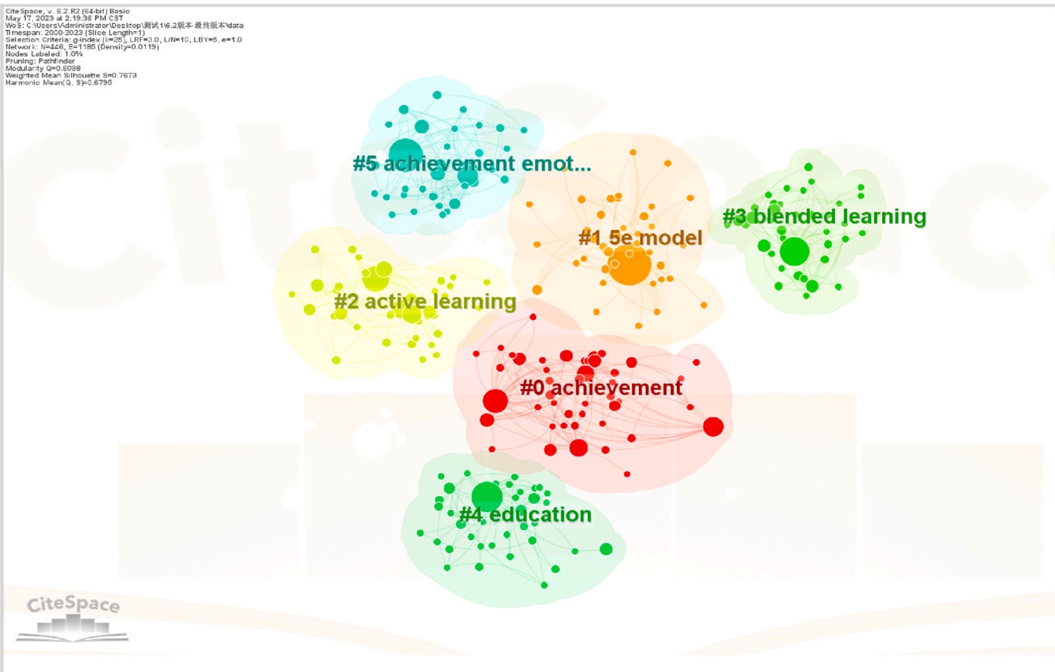

Fig. 7. Clustering of co-words for co-citation clustering.

between keywords. Therefore, we use CiteSpace clustering method to generate cluster identifiers of literature co-citation relationships by automatically extracting keywords or noun phrases from the cited literature to attribute research hotspots; each cluster can be considered as a relatively closely related independent research area [55]. CiteSpace uses two metrics to assess the effectiveness of clustering, Modularity (Q) and Silhouette (S). Q is an evaluation metric for network modularity, and a higher Q value indicates better network clustering. q takes the interval [0, 1], with $Q > 0.3$ indicating significant network structure. S is a metric used to measure network homogeneity, and the closer it is to 1, the more homogeneous the network is. When S is more significant than 0.7, the clustering result has high reliability, and if the value is above 0.5, the clustering result can be considered reasonable [36]. From Fig. 7, $Q = 0.6098$ and $S = 0.7673$ indicate that the clustering structure is prominent and highly reliable.

Fig. 7 shows only the top 6 clusters with a high number of citations and high homogeneity to maintain the clarity of the clusters. Table 5 summarizes information about these six clusters, including Cluster ID, Cluster label, Size, S-value, mean year, and alternative labels. The data in the table show that all clusters have S-values above 0.6, which indicates good clustering consistency. In order to better derive the research frontiers of LCM, the references frequently cited in these clusters were scrutinized by clustering them twice (Table 6), where the labels describing the nature of LCM (bscs 5e instructional model, instruction, 5e model, 5e learning cycle, 5e learning model, active learning, inquiry-based learning, education, students, science education, model, meaningful learning orientation) were no longer included in the secondary clusters Table 6.

4.3.1. *Cluster#1: LCM and science concept learning*

Concept learning is an essential field in science learning. Since the rise of constructivism in the 1980s, researchers in psychology and education have begun to pay attention to children's pre-concepts and their transformation into scientific concepts. Concept change research has become an international science education Research focus [53]. Currently, constructivist-based teaching strategies have been widely used to help students construct concepts and meaningful understanding and prevent pre-concepts [56]. As a teaching model based on constructivism, LCM provides opportunities to learn new concepts or deepen the understanding of known concepts. Reviewing the research on the impact of LCM on learners' conceptual learning, all show a typical result: LCM is effective in improving students' conceptual learning [57]. This conclusion is substantiated by the systematic review conducted by Joswick and his colleagues [16].

It is noteworthy that through cluster analysis and keyword co-citation analysis, we have identified a new emerging trend in the field of international scientific concept learning research. This trend signifies a shift from a predominant focus on "conceptual change" to a heightened emphasis on "conceptual understanding." Importantly, this evolving trend is reinforced by concurrent academic support and research [58]. Concept change theory proposes that four conditions must be met to achieve concept change: dissatisfaction with the original concept, understandability of the new concept, rationality of the new concept, and validity of the new concept. These four conditions are progressive in sequence, and the latter can only be achieved if the former is met. However, research shows that students often need help understanding scientific concepts, and students' understanding of scientific concepts is the key factor that restricts students' conceptual change [59]. Therefore, in the 1990s, the Zero Point Project, funded by the Spencer Fund and the Harvard Graduate School of Education, proposed "teaching for understanding," advocating teaching for understanding gradually became a trend in international educational research [60]. The teaching of conceptual understanding attaches great importance to students' thinking and emphasizes that concepts differ from facts. The teaching of conceptual understanding is to make students believe in the rationality of these concepts [61]. Research on scientific concept learning has shifted from "conceptual change" to "conceptual understanding," reflecting that science education pays more attention to teaching students how to acquire scientific concepts through thinking, which not only includes enriching knowledge structures but also training thinking activities [62].

4.3.2. *Cluster#2: LCM is used in different teaching process*

The LCM, which serves as a guiding framework for inquiry, can be further enriched by integrating various teaching processes. The literature we reviewed shows that some studies have embraced LCM in tandem with other teaching methodologies. Mehmet et al. pioneered the combination of the flipped classroom model with the 5E LCM, fostering students' scientific understanding and skills development in a hybrid and online learning environment [62]. Yasemin et al. employed analogy models alongside the 5E LCM to impart astronomy concepts, observing how this instructional approach empowers students to construct and refine their knowledge

Table 5
Summary of identified co-citation clusters.

Cluster ID	Cluster label	Size	Silhouette	Mean	Alternative label
0	Achievement	45	0.825	2014	Achievement; bscs 5e instructional model; electrochemistry; instruction; web-based information-searching
1	5e model	41	0.728	2015	5e model; 5e learning cycle; 5e learning model; design-based research; vision and change
2	Active learning	39	0.826	2013	active learning; conceptual understanding; inquiry-based learning; chemistry education; alternative conceptions
3	Blended learning	38	0.775	2017	blended learning; critical thinking skills; elementary school; respiration; cooperative learning
4	Education	37	0.662	2013	education; stem education; students; mathematics; concept understanding
5	Achievement emotions	45	0.824	2012	achievement emotions; learning motivation; science education; model; meaningful learning orientation

Table 6
Quadratic clustering.

Cluster ID	Cluster title	Include tags
1	LCM and science concept learning	electrochemistry、conceptual understanding、alternative conceptions、respiration
2	LCM is used in different teaching process	web-based information-searching、blended learning、stem education、 cooperative learning
3	Effectiveness studies of LCM	achievement、design based research、achievement emotions、learning motivation、critical thinking skills
4	The use of LCM in different disciplines	chemistry education、elementary school 、psychiatry、mathematics

actively [63].

Significantly, the application of LCM within STEM (Science, Technology, Engineering, and Mathematics) education emerges as a prevalent theme [35]. The K-12 science curriculum actively encourages educators to adopt STEM-oriented science teaching methods [64]. Numerous research findings also underscore the positive impact of the 5E LCM on students' performance within STEM education [65], leading to its identification as one of the most effective instructional models in STEM-focused science courses [66,67], often referred to as the "5E-based STEM model" (5E-STEM) [64]. Notably, in 2019, Bybee introduced the concept of a "5E-STEM model" in his article "Using the BSCS 5E Instructional Model to Introduce STEM Disciplines [68]." However, based on the search results from WOSCC, scholars still need to undertake research focused explicitly on this model. This observation prompts consideration of potential research avenues, such as comparative studies evaluating its effectiveness compared to other 5E-STEM models.

4.3.3. Cluster#3: effectiveness studies of LCM

The widespread adoption of the LCM prompted a call for original empirical research on its effectiveness by Bybee et al., in 2006 [31]. Since then, empirical studies evaluating the effectiveness of the LCM have progressively emerged. In recent years, a multitude of system reviews and meta-analyses concerning the LCM have been published, substantiating the heightened focus on researching its efficacy [16]. In 2015, Anil and Batdi [18] conducted a pioneering meta-analysis, comparing the impact of the 5E LCM with traditional teaching methods in Turkish literature. Their study assessed students' academic performance, memory retention, and attitudes, revealing that the 5E LCM positively influenced all three aspects. Subsequently, in 2022, Candace Joswick [16] and his colleagues conducted the first systematic review of empirical research on 5E LCM within K-20 mathematics and science education. Their findings confirmed the effectiveness of the 5E LCM in enhancing conceptual knowledge, and often demonstrated substantial efficacy in elevating attitudes and fostering interest in science. Furthermore, various comparative studies have assessed the influence of LCM on student attitudes. These studies consistently indicate that when LCM is employed in science fields such as chemistry [56], earth/space [63], and physics [57], it leads to improvements in students' understanding, attitudes, and motivation.

4.3.4. Cluster#4: the use of LCM in different disciplines

In 2013, the United States introduced the Next Generation Science Standards (NGSS) in response to the demands of economic development and the pursuit of international educational competitiveness. This pivotal initiative left a profound impact on American science education [69]. NGSS advocates that learning should be exploratory and developmental and strongly supports teachers to use LCM for classroom teaching. It emphasizes that scientific learning should be a process of sensory interaction. Teachers need to design

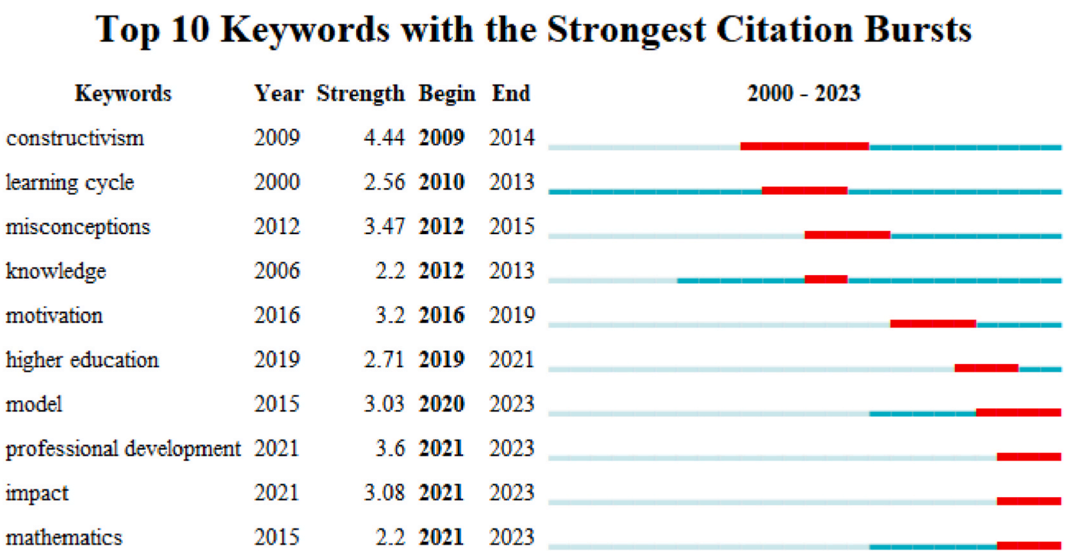

Fig. 8. Top 10 keywords with the strongest citation bursts.

cleverly and step by step to closely integrate science and engineering practice [70]. Presently, the application of LCM has transcended science disciplines, extending its influence into other domains such as mathematics [16] and nursing [71]. This expansion encompasses all educational stages, spanning from preschool education to higher education. It serves as a catalyst for meaningful learning and the development of students' scientific concepts, thereby facilitating the attainment of various educational objectives at each stage of teaching.

4.4. Future research trends in LCM

To delineate the evolving research frontiers within this field, this study leverages the software's built-in algorithm to pinpoint keyword bursts. Fig. 8 shows the top 10 burst keywords in the LCM study, including burst intensity, start year, end year, and duration. Keywords that surfaced before 2015 encompassed terms such as "constructivism," "learning cycle," "misconception," and "knowledge." Notably, "constructivism" emerged as the most prominent keyword in both intensity and duration.

A detailed scrutiny of these emergent keywords unveils two pivotal shifts within the domain of international foundational science education. In the early 1960s, international science curricula predominantly adhered to Jerome Brunauer's subject structure theory, emphasizing the structural organization of subjects, theoretical underpinnings, and exploratory teaching approaches in science courses [30]. While these novel curricula were notably scientific, they initially fell short of anticipated success and were even deemed a "failure [72]." The experiences and insights from the 1960s reform efforts underscored a disconnect between curriculum, instructional materials, and classroom teaching. Two principal factors contributed to this gap: insufficient research on children's learning traits and a dearth of pedagogical quality among educators [73]. Consequently, during the 1970s, with the educational philosophy paradigm shifting toward "child-centeredness," scholars introduced the influential constructivist learning theory. Inquiry-based teaching, grounded in constructivism, transcended the confines of children's "hands-on" inquiry activities or experiments and shifted its focus to addressing students' "preconceptions," "misconceptions," or "cognitive frameworks" in the exploration of scientific concepts [72].

Keywords such as "motivation" and "higher education" began to surface in 2016, signifying the burgeoning interest in exploring the effectiveness of LCM within the realm of higher education. The persistence of a keyword's burst period typically indicates its representation of the research forefront and the most recent research hotspot [22]. Fig. 8 reveals those terms like "model," "professional development," "impact," and "mathematics" have consistently featured over time, indicating that LCM research will continue to delve into these areas. "model" serves as a broad descriptor for the entire research field, while "mathematics" highlights the widespread attention garnered by the application of LCM within mathematics disciplines. Our next course of action involves conducting a comprehensive examination of literature associated with keywords "professional development" and "impact," thereby uncovering potential avenues for future research.

4.4.1. LCM for teacher professional development study

Professional Development (PD) for educators holds a pivotal role in nurturing high-quality science instruction within the realm of science education [74]. Presently, countries across the globe underscore the significance of bolstering teacher professional development. Within this landscape, the inquiry-based LCM assumes a crucial role in advancing educators' professional growth, playing a dual role in this process. Firstly, LCM serves to enhance teachers' cognitive capacities, fostering substantial improvements. Secondly, it offers valuable support for instructors in structuring classroom teaching and refining their pedagogical practices. Several studies have explored the impact of the 5E LCM on prospective teachers' comprehension of specific knowledge contexts. The findings consistently demonstrate the capacity of the 5E LCM to stimulate shifts in prospective teachers' conceptual reasoning [75]. Notably, Bybee et al. contend that the 5E LCM serves as a versatile framework for the planning, execution, and evaluation of both learning and teaching endeavors [31]. In parallel, it stands as a valuable tool for aiding educators in the meticulous planning, effective implementation, and comprehensive evaluation of their teaching methodologies [31]. These considerations prompt inquiries into whether empirical research has substantiated LCM's potential to genuinely enhance teachers' instructional processes. Furthermore, an exploration into the precise role that LCM plays in advancing teachers' professional development is warranted. Additionally, it is pertinent to delve into the challenges that educators may encounter while employing LCM [76], striving to attain a deeper understanding of the root causes of these challenges and the strategies for optimizing the practical implementation of LCM.

4.4.2. Research on the impact of LCM on learning outcomes

Learning can generally be categorized into three domains: a) the cognitive domain, which in terms of thinking skills includes the ability to remember, understand, apply, analyze, synthesize, and evaluate; b) the affective domain, which includes personality behaviors such as feelings, interests, attitudes, emotions, and values; and c) the psychomotor domain, which includes imitation, manipulation, precision, expression, and naturalization [77]. Current research predominantly gravitates towards quantifying the cognitive domain of LCM research subjects. However, a limited number of studies have initiated empirical investigations into students' learning attitudes and motivation. These factors wield substantial influence over students' learning outcomes. Nevin Kozcu Cakır [17], for instance, employed a meta-analysis approach to scrutinize literature related to the 5E LCM from 2006 to 2016. The findings revealed that when compared to traditional teaching methods, the 5E LCM exerts a moderate impact on students' attitudes toward courses. Likewise, Ayla and her team conducted empirical research employing the teaching experiment methodology to explore the effects of the 5E LCM on students' motivation to learn chemistry [56]. Their study unearthed a profound impact on learning motivation by increasing the relevance of chemistry knowledge to everyday life. Consequently, the implications of LCM on learning outcomes warrant further in-depth investigation. This includes research into whether LCM affects learning motivation and attitude across diverse subjects, alongside probing various facets of learning outcomes. These encompass enhancements in students' expressive abilities and heightened interest in learning. Empirical studies geared toward assessing these changes hold promise for advancing our understanding in this domain.

5. Discussion and conclusion

Since its development by Robert Karplus in the late 1950s, LCM has gradually evolved into a paradigm for science teaching and curriculum design [78]. Yet, the popularity of the LCM extends to content and levels beyond elementary science. A clear indicator of this growth is evident in the burgeoning volume of LCM related studies over the past five years. Within this crucial juncture that melds research and practical application, there is a compelling need to conduct a comprehensive tracking and visual analysis of LCM research. Such an endeavor serves the invaluable purpose of furnishing pertinent researchers and practitioners with a comprehensive and up-to-date overview of the latest developments in LCM research. This study uses CiteSpace (6.2.R2) to conduct visual analysis on 498 papers related to LCM research included in the WOSCC from 2000 to 2023, draw a visual map of LCM research, and examine the basic characteristics and research hotspots of this field. and trend evolution. Through this research, it can be found:

First, the mapping analysis highlights the current robust expansion of the LCM research field. Although the reasons for this trend are diverse, based on the content and methodologies found in the literature, the LCM field is becoming increasingly comprehensive, indicating a global upsurge in interest in LCM education. The United States primarily contributes to this field, far exceeding other nations' publication volume. This significance underscores the significant role played by the U.S. in advancing LCM research and its application within educational contexts. Furthermore, the steady growth of Turkey's publication output in successive years deserves attention, indicating the nation's increasing commitment to science education. Exploring the factors underpinning this growth can provide valuable insights for regions aspiring to enhance science education by adopting LCM.

Second, the analysis map reveals that LCM research exhibits a relatively dispersed nature. Across various countries, the bulk of research occurs within university settings, with limited collaboration between universities, institutions, or experts and scholars. Consequently, an analysis of article authors reveals that a cohesive core author group has yet to fully materialize. However, certain authors, such as Nevin Kozcu Cakir and Salih Çepni, have already garnered influence in this field. This observation underscores the potential for future LCM research development through heightened collaboration, both regionally and among authors. Fostering stronger partnerships between researchers and institutions holds the promise of enhancing knowledge exchange, synergistic research endeavors, and the cultivation of a more unified and impactful LCM research community. Such collaborative efforts can drive the field forward and more effectively address emerging challenges and opportunities.

Third, a scrutiny of high-frequency keywords and keyword clustering maps elucidates the establishment of relatively stable research topics within LCM. Current research hotspots predominantly revolve around the effectiveness of LCM, its application in scientific concept learning, its integration with diverse learning processes, and its use across various disciplines. Moreover, as the educational landscape evolves, research methodologies have evolved significantly. The transition from early qualitative research methods to quantitative approaches reflects the growing demand for evidence-based educational practices. Researchers have now shifted their focus towards empirical investigations into the impact of LCM on student learning outcomes, including academic performance, and learning attitudes. This trend mirrors the growing impetus towards data-driven decision-making in education. Furthermore, LCM has transcended its single form in the classroom, actively infiltrating other educational processes to expand its application, thus enriching educational diversity and engagement. This trend not only broadens educational choices but also provides students with more inspiring and engaging learning modalities.

Fourth, through emergent detection, we unearth forthcoming trends in LCM research. These trends encompass research on the influence of LCM on teachers' professional development and learning outcomes. Additionally, we anticipate methodological advancements and practical applications to play an increasing role in LCM research. Methodological progress will encompass diversified research techniques such as mixed methods research and longitudinal research designs. These approaches will comprehensively assess LCM's impact on the learning process. Concurrently, as information technology proliferates, fields like virtual education and online learning will facilitate further practical applications of LCM. The future envisions LCM being extensively employed in various educational contexts, including flipped classrooms and online learning platforms, to enhance learners' conceptual understanding and motivation.

In conclusion, this study pioneers the application of bibliometric analysis to unveil historical research trends in the realm of LCM. The insights gleaned from this endeavor are invaluable for the development of teaching strategies and curriculum models grounded in LCM. This review amalgamates research forces, focal topics, and evolutionary trends in LCM research since the inception of the new century. It empowers educational practitioners with a profound comprehension of LCM, facilitating its more effective application and enhancement of students' learning outcomes. The thematic analysis of LCM research elucidates both areas of extensive exploration and domains requiring further investigation. This guidance empowers educational researchers to select appropriate research directions and continually refine and advance educational strategies rooted in LCM. Furthermore, the cutting-edge analysis unravels the current research hotspots in LCM, sparking the curiosity of educational practitioners and researchers and catalyzing in-depth research and innovation. These insights pave the way for the evolution of teaching strategies and curriculum models based on LCM, furthering students' conceptual understanding and learning motivation in the realm of education.

6. Limitations and future research

As an actively evolving and theoretically profound area of research, LCM research holds substantial developmental promise. The ongoing technological advancements suggest expansive prospects for LCM research in this era of transformation. Considering the foregoing, we propose the following avenues for future research.

6.1. Empirical investigation of LCM's impact on 21st century skills

In the swiftly changing, technology-driven global knowledge economy of the 21st century, there is a heightened emphasis on fostering skills that adapt to novel economic and societal paradigms. Internationally, there is consensus that higher-order thinking skills form the core educational objective for the 21st century [79]. As Rodger Bybee asserted in his research, LCM provides robust support for nurturing students' 21st century skills, encompassing adaptability, communication, problem-solving, self-management, and other abilities pertinent to adapting to society's rapid evolution [33]. Remarkably, nearly all the skills entailed in 21st century competence closely align with the specific implementation of the 5E LCM (refer to Table 7). While substantial research has explored LCM's effect on cognitive skills, the assessment of 21st century skills remain relatively underexplored. This gap may stem from a lack of suitable measurement tools [80]. Developing novel measurement instruments to comprehensively gauge LCM's efficacy in promoting 21st century skills is a worthwhile avenue for future research. This endeavor holds the potential to ensure LCM's ongoing contributions to education, better preparing students to meet the ever-evolving social and professional challenges of the 21st century.

6.2. Comparison of LCM with different inquiry-based learning models

While numerous studies affirm the effectiveness of LCM in education, there remains a dearth of comparative investigations with other inquiry-based learning models (e.g., case-based, project-based, or problem-based learning). These inquiry-based learning modalities share the goal of cultivating inquiry skills with LCM, actively guiding students in proactive exploration and learning during problem-solving. However, it has been noted that existing LCM research often lacks adequate detail regarding the implementation of LCM teaching, impeding determinations about which teaching methods (e.g., cooperative learning) or specific activity sequences can optimize LCM's potential [80]. Consequently, future research can significantly advance this field by conducting more comprehensive comparisons of LCM's educational impact with that of other inquiry-based learning methods across diverse aspects of student learning. This approach will provide education decision-makers with more precise insights to optimize the selection and design of educational models, aligning them with evolving learning requisites and teaching environments.

6.3. Application of LCM to engineering education

Presently, while the application of LCM to STEM education has gained traction, most studies focus on STEM teaching rooted in the nature of science, overlooking the distinct domain of engineering. Some researchers have voiced concerns about the integration of engineering into science curricula due to their fundamental differences in ontology and cognitive concepts [81]. Recent developments guided by STEM education principles have introduced engineering practice into the innovative science education paradigm, heralding a new phase of science education reform worldwide [82]. Engineering affords students fresh educational opportunities but simultaneously presents challenges in conceptualizing disciplinary core concepts, interdisciplinary notions, and scientific and engineering practices within the engineering domain. In this context, LCM, as a mature concept learning methodology, dissects the process of acquiring new concepts into three pivotal stages: exploration, acquisition, and application, fostering learners' cognitive development throughout a complete LCM. In the technology and engineering sphere, the application and evolution of LCM hold significant reference value and offer potential avenues for teaching the core tenets of the subject.

While this study offers valuable insights, it bears certain limitations. Our analysis exclusively encompassed literature from the WOSCC, potentially omitting relevant research from other databases such as Scopus. Future research endeavors will merge Scopus and WOS to produce more comprehensive bibliometric research outcomes, leveraging the strengths of both sources. Secondly, our analysis, at a macro-level evaluation, does not assess the individual merit of each document. Subsequent research may explore a combined approach, integrating systematic reviews to holistically assess the research literature. Finally, cluster analysis was confined to the scrutiny of the initial six clustered samples, exhibiting a degree of subjectivity. Future research will build upon this foundation, delving into more profound literature analysis and further research scrutiny to gain a more detailed understanding of research pathways.

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Table 7
Linkages and the effectiveness of the BSCS 5E instructional model with 21st century skills [33].

GOAL OF 21ST CENTURY SKILL	BSCS 5E INSTRUCTIONAL MODEL
ADAPTABILITY	Inadequate Evidence
COMPLEX-COMMUNICATION	Some Evidence Based on Argumentation
NON-ROUTINE PROBLEM SOLVING	Strong Evidence Based on Scientific Reasoning
SELF MANAGEMENT/SELF DEVELOPMENT	Strong Evidence Based on Attitudes Toward and Interest in Science
SYSTEMS THINKING	Strong Evidence Based on Mastery of Scientific Knowledge

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Data availability statement

The authors do not have permission to share data.

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Min Jian: Conceptualization, Methodology, Visualization, Writing – original draft. **Xiaopeng Wu:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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