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Review

Research on Online Collaborative Problem-Solving in the Last 10 Years: Current Status, Hotspots, and Outlook—A Knowledge Graph Analysis Based on CiteSpace

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Abstract: Collaborative problem-solving is a crucial skill to be developed in education. With the development of information technology, collaborative problem-solving in online environments has received increasing attention in recent years. There has been some foundation of research on computer-supported collaborative learning (CSCL) and collaborative problem-solving (CPS). They both have a focus, but there is a trend to combine them. Further understanding of the current state of research on online collaborative problem-solving is much needed. This study reviews 528 relevant papers from the last decade. The researchers summarized the current state of research and hotspots in online collaborative problem-solving based on the visual analysis of CiteSpace. It was found that the number of papers on online collaborative problem-solving is on the rise, with CPS and CSCL as the main research content and 'feature extraction', 'task analysis', and 'computation modeling' as the hot research topics in the past three years. The current research power on CPS and CSCL is mainly distributed in China and the United States, but the inter-institutional collaboration is little. Based on the research results, this paper proposes four future directions to improve the research in online collaborative problem-solving: identity awareness in online collaborative problem-solving, interdisciplinary online collaborative problem-solving, online collaborative problem-solving for teachers, and online collaborative problem-solving and ICT skills.

Keywords: online collaboration; problem-solving; learning methods; computer-assisted instruction; information and communication technology

MSC: 97C80

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1. Introduction

In the digital age, information and communication technology is rapidly developing. Electronic technology's interaction, control, and connectivity have brought about significant changes in mathematics learning, which connects teachers and teachers, teachers and students, and students and students [1], and runs through all the future research themes of mathematics education [2]. Problem-solving ability is one of the main manifestations of students' comprehensive quality. Cultivating students' problem-solving abilities is the primary goal of contemporary educators. Educators seek different ways to encourage students to participate in problem-centered learning [3] and seek how to support better collaboration to produce higher-level learning [4]. In the eyes of educational researchers, communication and collaborative problem-solving (CPS) are regarded as critical skills in the 21st century [5], and computer-supported collaborative learning (CSCL) and CPS have attracted widespread attention [6].

CSCL, which aims at knowledge sharing and co-construction [7], is a teamwork method of technical support. It involves meaningful interaction with others based on common goals and ultimately improves social skills and the ability to comprehensively use the information for innovation. CSCL attempts to promote knowledge construction through social interaction. Compared with lecturing teaching, computer-supported collaborative inquiry learning [8] is a popular teaching method. As is known, discussion teaching is often used to develop students' cognitive skills and critical thinking [9]. The discussion teaching method has received a lot of attention. At the same time, problem-solving teaching is also recognized as a superior teaching strategy [10], which is worthy of educators to practice and explore in the CSCL environment. However, social interaction in CSCL is limited by technology, interaction patterns, and social distancing, and students have a low sense of social presence [11]. In addition, building group norms, trust, and community belonging in an online environment is more challenging [12]. Therefore, the research on effectively using computers to support collaborative learning still needs further development [13].

CPS refers to the process in which individuals work together to develop solutions by sharing knowledge and skills with others to effectively participate in the problem-solving process [14]. The ability to solve problems is one of the core competencies that citizens should have in this digital age of the 21st century [15]. Students who move from school to society are expected to have the ability to use appropriate technology for CPS. CPS has received more attention and has been incorporated into large-scale international and computer-supported learning assessments [16]. The PISA2015 assessment and analysis framework [14] describes the basic principles of CPS skills and explains the contents and processes reflected in collaborative problem-solving projects used in computer-based assessment. Especially in higher education, many innovative approaches and techniques have been adopted to develop students' collaborative problem-solving skills, including project-based learning [17], immersive techniques [18], and online collaborative learning. Research has shown that the close integration of the collaborative learning process with problem-solving processes can produce a good learning performance [19].

Compared with problem-solving, CPS has the advantages of collaboration, including effective division of labor, absorption of information from multiple sources, and collective improvement of creativity and solution quality. The best sharing of resources is the key to the smooth progress of CPS [20]. CPS allows us to find necessary external resources through cooperation when individual or collective resources are insufficient [21]. Classic studies [22,23] have shown that collaborative groups can build deeper learning by participating in constructive, critical, respectful, and cohesive interactions.

Both CPS and CSCL teaching strategies promote educational equity and improve educational quality. They all need to pay more attention to the mutual development of cognitive and social skills and inevitably have a more profound combination with technology. This research considers online collaborative problem-solving as collaborative problem-solving learning in the online environment. Online collaborative problem-solving combines problem-based collaborative learning and online learning, and it is computer-supported collaborative problem-solving. Online collaborative problem-solving has the following characteristics:

- Computer-supported collaborative learning,
- The goal of the collaboration is to solve problems,
- To support asynchronous creation, sharing, experience transfer, and guidance,
- Participants experience cognitive and social interaction processes.

The education field has experienced the impacts of the global pandemic, so online and offline hybrid teaching has been valued. Online collaborative problem-solving provides an innovative way of teaching and learning, reflecting technology's promotion of education. Specifically, online collaborative problem-solving can develop students' 21st-century skills [24], including information and communication technology (ICT), problem-solving, critical thinking, communication, and collaboration. The practice of most researchers has

proved that the computer is an effective way to support CPS. In a computer-supported CPS environment, participants can better understand learning topics [25].

2. Research Problems

In recent years, there have been many collaborative problem-solving practices with the help of an online environment. Researchers have analyzed the collaborative problem-solving process in an online environment from various angles but have paid little attention to the potential impact of technology on collaborative problem-solving [26], ignoring the educational background of collaboration [27], and have lacked a comprehensive macro-perspective on understanding the combination of CSCL and CPS. Therefore, the research in the online collaborative problem-solving field is worth combing systematically, and future development trends in research are worth exploring. In this study, the authors of this paper have analyzed the knowledge graph of online collaborative problem-solving research in the past 10 years through CiteSpace, looking for an answer to the following questions:

(1) What is the research status of online collaborative problem-solving?
(2) What are the research hotspots of online collaborative problem-solving?

3. Materials and Methods

The data of this study come from the core collection of the Web of Science. The researchers input the words 'online collaborative problem-solving', set the retrieval time range from 2012 to 2022, selected 'Article', screened the literature in education and educational research, and then selected 528 articles by manual screening. A bibliometric analysis of the collected literature data was performed to directly show the research status and hotspots of online collaborative problem-solving. Bibliometric analysis refers to the quantitative analysis of the cross-science of all knowledge carriers through mathematics and statistics. It is a comprehensive knowledge system integrating mathematics, statistics, and philology. It pays attention to quantification. The primary measurement objects are the amount of literature (all kinds of publications, especially periodical papers, and citations), the number of authors (individuals or groups), and so on [28].

Under the guidance of this method, this study took 528 papers as the analysis objects and drew a knowledge graph with the help of CiteSpace (6.1.R4) visual analysis. CiteSpace is an information visualization software developed by Professor Chen Chaomei of Drexel University based on Java in 2004. It can visually analyze many related documents, such as countries, institutions, authors, keywords, and co-citations, and shows the development trend and trend of a particular research field in a certain period [29]. The research basis and status are shown through the visual analysis of the number of articles published by authors, countries, and institutions. The research hotspots are shown by keyword analysis and cluster analysis. Literature analysis was to extract the selected papers' themes to discover research hotspots. Literature analysis refers to exploring the research hotspot of online collaborative problems by studying the collected literature data and drawing the findings.

4. Results

4.1. Research Status

4.1.1. Number of Papers Published

The changing number of papers can directly reflect the development of online collaborative problem-solving. Generally speaking, the more papers published, the deeper the research in the field and the more attention the field has received. It can be seen from Figure 1 that the annual collection of literature in the WOS core collection shows an increasing trend year-by-year. The number of papers published from 2012 to 2015 was relatively small, and the trend was stable. It increased significantly after 2015. Online collaborative problem-solving gradually began to receive more and more attention from society and researchers. In the 2015 International Student Assessment Program (PISA) cycle, the assessment included a computerized measurement of collaborative problem-solving skills (CPS) using virtual agents. PISA is the most extensive assessment of a student's academic and

general abilities worldwide. Its results can influence the change in education policy and the reform of school teaching [30]. It can be seen that online collaborative problem-solving ability was regarded as an essential quality.

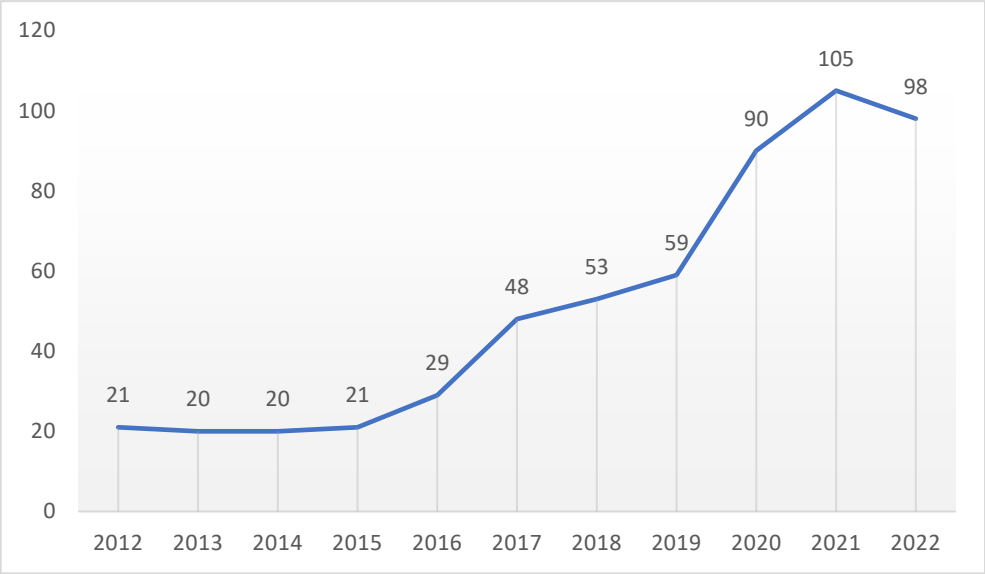

Figure 1. The number of papers published on online collaborative problem-solving in the WOS from 2012 to 2022.

In the case of international cooperation, collaborative problem-solving has been recognized as a vital ability for modern citizens. Learners need to form collaborative problem-solving abilities, which is also a concern for educators [31]. PISA2015's assessment involved online collaborative problem-solving, which attracted more attention and exploration in this field. In 2017–2019, the growth rate of the literature slowed down. During the pandemic in 2020, the literature showed a significant growth trend again, reaching a peak in 2021. During this period, online work became the primary way of working around the world, and the research on online collaborative problem-solving also rapidly increased. With the rapid development of information technology, communication technology increasingly provides synchronous and asynchronous technology tools to support more abstract collaboration. Technology-mediated or computer-supported collaborative learning (CSCL) promotes a new paradigm [32]. It also means that research on online collaborative problem-solving has upward potential in the post-pandemic era and the era of pandemic recovery.

4.1.2. Authors with High Citation Rates

To better understand the distribution of research power in online collaborative problem-solving, the top ten authors with cumulative citation frequency since 2012 were counted, as shown in Table 1. The cumulative cited frequency of the authors in Table 1 is more than 15 times. Knowing highly cited authors on a research topic helps us gain insight into the research field.

In this paper, the researchers briefly analyzed the research of the top three authors. If the readers are interested in more research, they can consult the relevant articles of the other authors through the list. At the top of the list (Table 1) is the Organization for Economic Cooperation and Development (OECD), with a cumulative cited frequency of 28. The OECD is an international organization of 34 countries, including Canada and the United States, headquartered in Paris, France. In 2000, the OECD launched a triennial assessment project focusing on reading, math, and science, called PISA (Program for International Student Assessment), focusing on the knowledge of 15-year-olds in these areas [33]. In 2012, the project added a problem-solving assessment to its evaluation project, focusing on how students acquire the critical knowledge and skills necessary to fully participate in modern

society. The project not only determined whether they could master what they had learned but also examined their ability to apply it in real life [34]. In 2015, the PISA program not only measured the extent to which 15-year-olds acquired basic knowledge and abilities but also included projects to explore students' attitudes towards science to improve our understanding of why students perform well in areas of knowledge and competence [35], as well as collaborative problem-solving.

Table 1. Highly cited authors in online collaborative problem-solving research from 2012 to 2022.

Ranking	Author/Organization	Frequency
1	OECD	28
2	Hmelo-Silver C.E	24
3	Hou H.T	20
4	Roschelle J	20
5	Jonassen D.H	19
6	Griffin P	16
7	Braun Virginia	16
8	Jeong H	15
9	Koren Y	15
10	Hesse F	15

A survey by the author Hmelo-Silver C.E has been cited 24 times in the Web of Science, which is representative. The survey tracks the problem-solving process of online collaborative modeling and explains the complex interaction patterns of collaboration in a computer-based learning environment. In addition, concerning the tools and content of online collaborative problem-solving, the results show that teamwork and interaction are better when using the Mental Modeler to plan and simulate citizen science projects for discussion [36].

The author Hou H.T's main research field is the effective combination of computer and education teaching. In recent years, his research has involved combining games and education and the online environment development of collaborative problem-solving, with rich research results.

4.1.3. Highly Cited Journals

Analyzing the cited journals of online collaborative problem-solving research can somewhat illustrate the main academic contributions in this field. Statistics show that since 2012, 528 research papers with the theme of "online collaborative problem-solving" have been mainly published in more than 100 international core journals. Generally speaking, many international publications on online collaborative problem-solving cover a relatively wide range, and the research field is relatively scattered.

This study lists the names of 10 journals with more than 50 articles cited (Table 2). Here, some of these journals are briefly introduced, and the rest serve as indexes for interested readers to dig deeper. According to the source of the journals, most journals belong to computer and educational technology. The research results of online collaborative problem-solving in international academic circles mainly focus on computer-assisted instruction.

The number one journal is *Computer & Education*. The journal aims to increase the understanding of how digital technology promotes education by publishing high-quality research results that expand theory and practice [37]. Computing and communication technologies increasingly impact all cognition, education, and training, especially in the evolving open and distance learning environment. The journal has been included in the international authoritative databases SSCI and SCI. It is committed to publishing high-quality, strictly peer-reviewed articles, reflecting engineering technology for computers: new progress, new technologies, and achievements in interdisciplinary application fields, and promoting scientific research exchanges and transformation of scientific research achievements in this field. The influence factor of the journal in 2023 is 11.182.

The second-ranked journal is *Computers in Human Behavior*. The journal is dedicated to studying the use of computers from a psychological perspective. It publishes original theoretical works, research reports, literature reviews, comprehensive software reviews, book reviews, and announcements. The journal discusses the use of computers in psychology, psychiatry, and related disciplines, as well as the psychological impact of computer use on individuals, groups, and society.

Most remaining journals are also in computer science and educational technology, accessible to readers. The research results of the international academia on online collaborative problem-solving focus on computer-aided teaching [38]. It is not difficult to find that the journals listed in the table are all related to computer or information technology applications.

Table 2. The journals with many online collaborative problem-solving articles published in 2012–2022.

Ranking	Journal	Frequency
1	COMPUT EDUC	154
2	COMPUT HUM BEHAV	119
3	LECT NOTES COMPUT SC	105
4	ETR&D-EDUC TECH RES	84
5	EDUC TECHNOL SOC	69
6	IEEE ACCESS	68
7	BRIT J EDUC TECHNOL	63
8	EXPERT SYST APPL	63
9	INT J COMP-SUPP COLL	62
10	J COMPUT ASSIST LEAR	58

4.1.4. The Regional Distribution of the Studies

Through the distribution of countries and institutions in the research field, it is helpful to clarify the distribution of scientific research forces in this field and play a guiding role in future learning and cooperation. This study visualizes countries and institutions that have studied online collaborative problem-solving through *CiteSpace*. The study found that China and the United States had the most published articles. This means that researchers in China and the United States have performed a lot of exploration on online collaborative problem-solving.

It can be seen from Table 3 that there are 232 articles based in China and 158 articles in the United States, while the number of papers issued by Australia in this field is significantly reduced, with only slightly more than 30, which is a considerable gap between the first two countries. China and the United States are more interested in research in the online collaborative problem-solving field and have made some achievements. Both countries have published more than 150 articles. Besides, eight other countries are also interested in online collaborative problem-solving and have more than thirteen articles, including Canada, the United Kingdom, and Germany.

Table 3. The top 10 countries/regions regarding the volume of online collaborative problem-solving articles in WOS from 2012 to 2022.

Ranking	Country	Frequency
1	China	232
2	USA	158
3	Australia	36
4	Canada	30
5	England	29
6	Germany	23
7	Spain	17
8	Netherlands	15
9	South Korea	14
10	Singapore	13

In the co-occurrence map of Figure 2, the node size represents the number of publications in the country/region. The larger the node, the higher the number of publications, and the purple circle outside the node indicates that the node has intermediary centrality. The wider the color band, the stronger the intermediary, which means the node is an important hub connecting different fields. The figure shows seven countries with intermediary centrality: China, the United States, Britain, Australia, the Netherlands, Scotland, and Saudi Arabia. There are some exchanges between these countries in online collaborative problem-solving, which is conducive to promoting the development of this field.

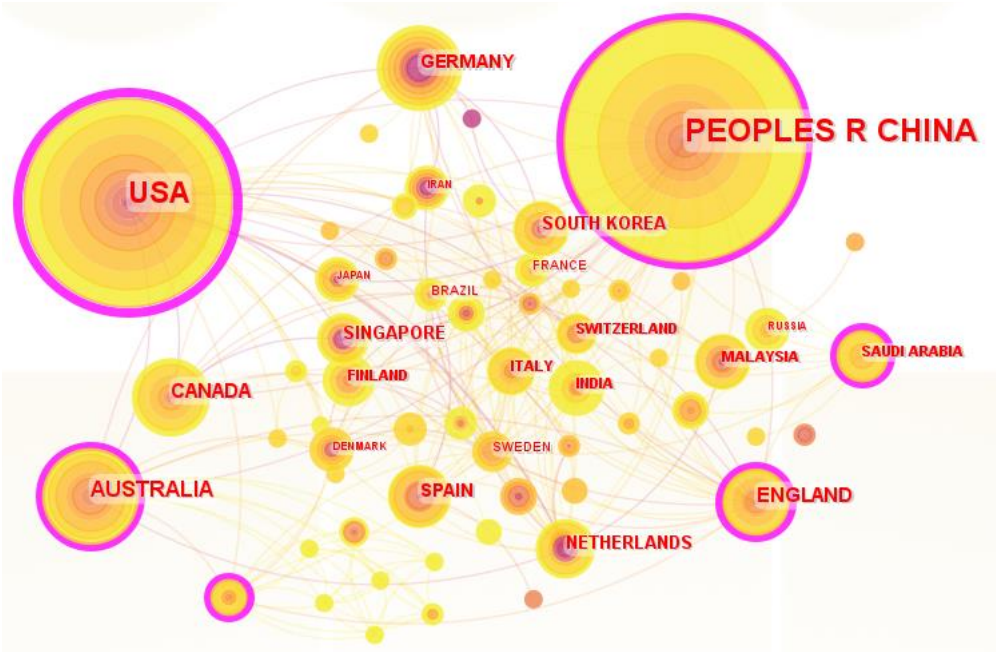

Figure 2. The co-occurrence map of the top 10 countries/regions.

The top three institutions in terms of publication volume are the Central China Normal University, the National Taiwan University of Science and Technology, and the University of Melbourne (Table 4). Institutions with a high volume of articles are not only the main base of online collaborative problem-solving but also the research position of the core author group, thus demonstrating their more significant academic influence. The number 1 institution, the Central China Normal University, began publishing its first articles in the field in 2017, when the number of publications significantly increased. Most articles were published in 2022, including articles about virtual community, identity cognition, multimodel analysis of online collaborative problem-solving, collaborative problem-solving ability of students and teachers, and group interaction and cognitive status in the online collaborative problem-solving process. These articles use various methods to solve research problems, such as text mining, content analysis, multimodal analysis systems, and other methods to analyze a series of problems in online collaborative problem-solving. The organization has made an essential contribution to developing online collaborative issues.

Figure 3 shows the co-occurrence map of each organization, and the size of different nodes represents the number of articles sent by the organization. The co-occurrence map shows that the intermediate centrality of these nodes is less than 0.1, so there is no purple circle outside the nodes. It shows that although there is a certain degree of cooperation among various agencies, there is little cooperation and no vital hub. Cooperation can be strengthened to contribute more to online collaborative problem-solving research.

Table 4. The top 10 institutions by the volume of online collaborative problem-solving articles in the WOS from 2012 to 2022.

Ranking	Institution	Frequency
1	Central China Normal University	8
2	National Taiwan University of Science and Technology	7
3	University of Melbourne	7
4	Zhejiang University	7
5	Nanyang Technological University	7
6	Beijing Normal University	7
7	Tsinghua University	6
8	Beijing University of Posts and Telecommunication	5
9	Beijing Jiaotong University	5
10	Chinese Academy of Science	5

Figure 3. The co-occurrence map of institutional publications on online collaborative problem-solving in the WOS in 2012–2022.

4.1.5. Co-Citation Analysis

Co-citation analysis was performed for the 528 articles. Literature co-citation refers to two or more articles being cited by one or more later papers, simultaneously, so it is said that these two or more papers constitute the co-citation relationship. Through the network research of literature co-citation, we can understand the research basis in the research field of the literature.

As can be seen from Figure 4, the most cited article is "A framework for teachable collaborative problem-solving skills" published in 2015, with a total of 10 citations. This article is part of the Educational Assessment Series in the Information Age, mainly introducing a conceptual framework for collaborative problem-solving. The framework informed findings from different research areas, such as cognitive science, education, social psychology, and psycholinguistics, to inform the design of collaborative problem-solving tasks. These tasks

involve as many identified skillsets as possible. Once the results of these tasks are available, the theoretical hypotheses under the framework can be tested to validate or refine the framework, thereby deepening the understanding of collaborative problem-solving [39]. This article makes an essential contribution to the research in collaborative problem-solving, and it also has an important guiding significance for the research in online collaborative problem-solving.

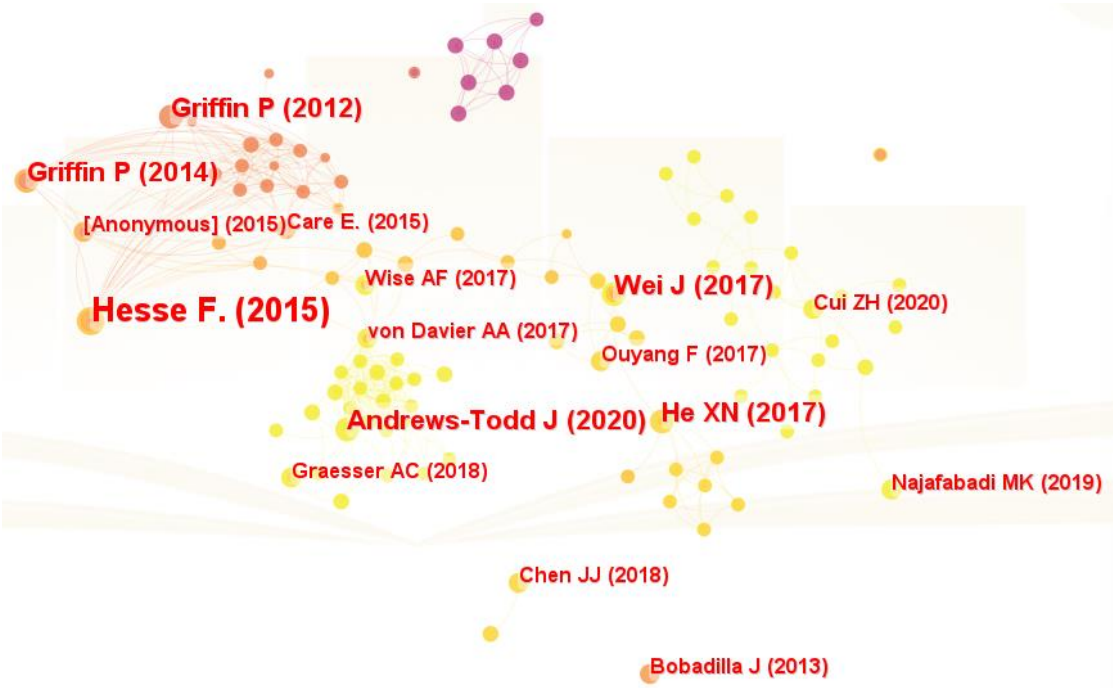

Figure 4. The co-occurrence map of literature co-citations.

The node in the figure represents the published article. The larger the node, the more times the article is cited. The connection between the nodes represents the strength of the literature's total citations, and the wider the connection, the greater the strength.

4.2. Research Hotspot

4.2.1. International Research Frontier

Figure 5 shows the keyword emergence intensity. Generally, the greater the intensity of keyword emergence, the higher the degree of attention to the keyword. The keywords with the highest emergence intensity were 'online', with an intensity of 4.16, followed by 'science', with an emergence intensity of 2.75, and the third was 'pattern', with an emergence intensity of 2.68.

The research hotspots on online collaborative problem-solving in the past three years include 'feature extraction', 'task analysis', 'outcome', and 'computation modeling'.

'Feature extraction' means extracting emotion from the speaker's speech signal in speech communication [40]. It indicates that recognizing and extracting participants' emotional features are becoming increasingly important in online collaborative problem-solving research. At the same time, language analysis is also a common way to investigate learning behavior.

'Task analysis' is an evidence-based practice that provides direction and guidance in inclusive environments [41]. Network platforms provide an inclusive environment, and collaborative problem-solving is task-oriented, so task analysis and design is a research hotspot in online collaborative problem-solving.

'Outcome' is the result, feedback, and evaluation research of online collaborative problem-solving. Since collaborative problem-solving (CPS) is a complex structure composed of skills related to social and cognitive dimensions, the various skills in these dimensions make CPS challenging to measure [42]. Therefore, the result evaluation of online

collaborative problem-solving is also the focus of the research due to its difficulty, which needs further research.

'Computation modeling' is one of the methods of online collaborative problem-solving, in which participants use computers to model and programs to solve problems.

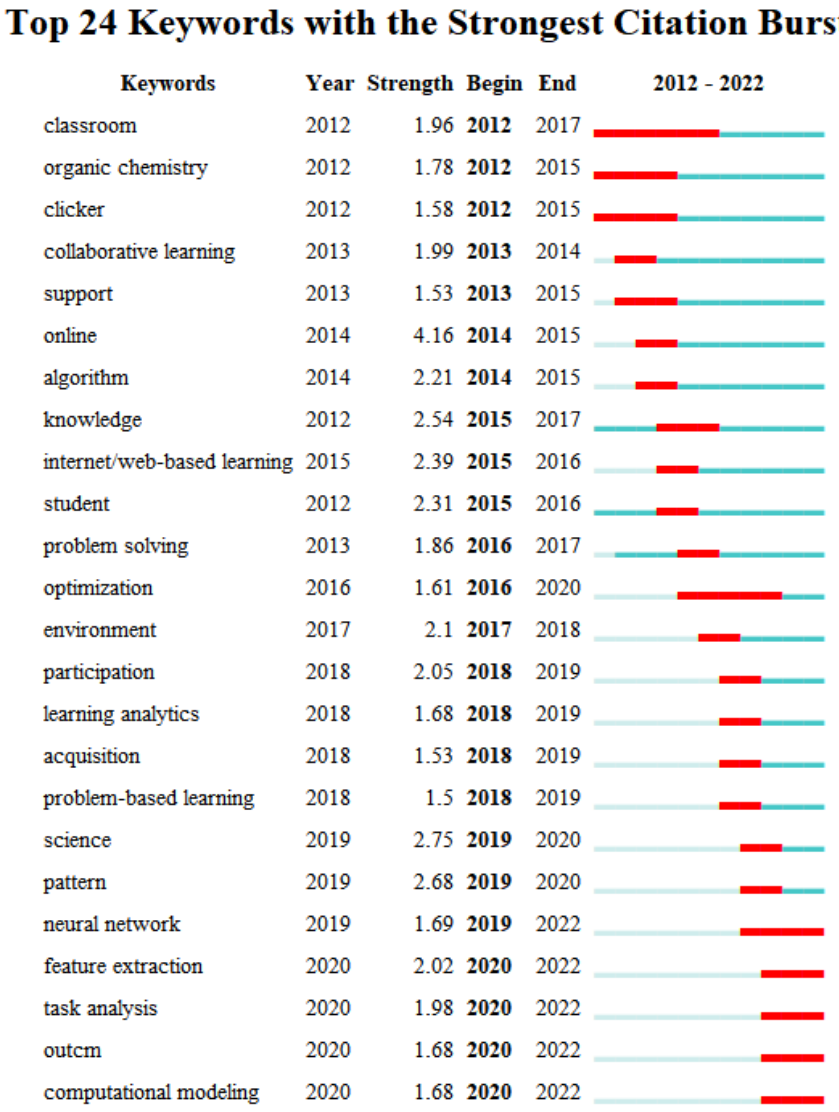

Figure 5. The keyword emergence map of online collaborative problem-solving from 2012 to 2022.

4.2.2. Cluster Analysis

Through the cluster analysis, it was found that the module value of the cluster map was 0.92 (>0.3), and the average profile value was 0.98 (>0.7), which indicated that the clustering result was reasonable. Using keywords and the LLR algorithm to extract clustering tags, nine results were obtained. The clustering result was inversely proportional to the size, and the largest cluster was marked with #0. The tags of these nine clusters are collaborative, collaborative problem-solving, computer-supported collaborative learning, collaborative filtering, multidisciplinary groups, object tracking, audience detection, enterprise education, and task analysis, respectively. The nodes in Figure 6 represent the published articles. The larger the node, the more the keywords were used, and different colored blocks represent the clustering generated by the keywords.

According to the map's ranking of the cluster nodes, the relevant identification words and literature were selected for research. It is believed that online collaborative problem-solving from 2012 to 2022 mainly focuses on the following two aspects.

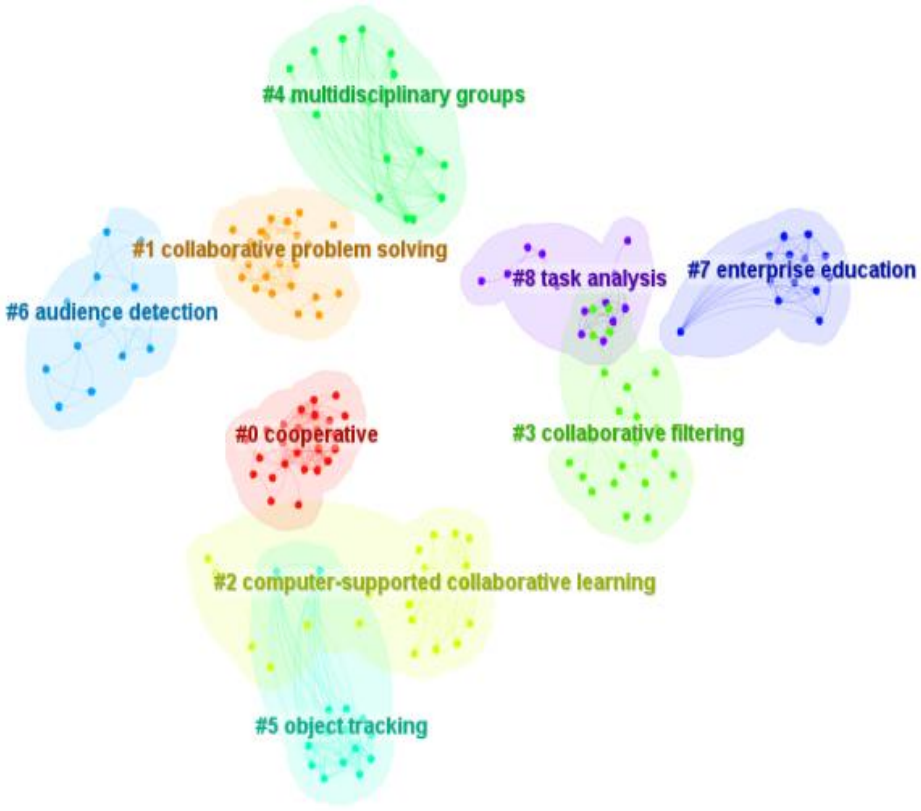

Figure 6. The cluster analysis of the online collaborative problem-solving domain from 2012 to 2022.

Collaborative problem-solving. Cooperation is the basis of online collaborative problem-solving. The effectiveness of collaborative learning has been widely recognized in the research community and has been proven to be more beneficial to academic achievement [43]. Collaborative problem-solving is increasingly recognized as a fundamental skill for students. Many related studies include sizeable international assessment programs, such as 21st Century Skills Assessment and Teaching (ATC21S), the International Student Assessment Program, and the Australian Curriculum Collaborative Problem-Solving Assessment. They have conducted special assessments on collaborative problem-solving capabilities [44]. ATC21S [45] further divides CPS into cognitive skills and social skills. Cognitive skills refer to the problem-solving part of CPS, while social skills refer to the collaborative part of CPS.

Complex problem-solving is a cognitive activity [46], but collaborative problem-solving is much more than that. Cognitive and social factors significantly influence the process of CPS [41], and knowledge does not dominate the interaction. Still, it plays a role at a specific time as the activity continues [47]. Hou [48], through a case study of the cognitive and behavior models of online collaborative problem-solving, found that when learning activities involve role-playing activities, the quality of discussion is better, and the solutions are more diverse.

However, learners lack cognition in application, evaluation, and innovation. Therefore, cognitive skills and social skills should complement each other. From the summary of collaborative learning research by Pieere (2007), we know that the theoretical focus of collaborative learning has shifted from the role of the individual to the group itself [49]. In future collaborative learning, connecting individual learning with speech interaction is necessary. Zheng [25] uses the sequence analysis method to study learners' behavior patterns from the interaction perspective and finds that conflicting views are conducive to in-depth exploratory discussion and promote problem-solving.

Computer-supported collaborative learning. In the past, online communication was asynchronous and text-based. With the development of technology, it is possible to use rich synchronous communication tools to support online learning, similar to face-to-face interaction through audio, video, and chat [50]. A computer-supported learning environment is formed. Collaborative learning in this environment usually means learners complete tasks together and gain knowledge by discussing their personal views through text-based media or videoconferencing [51]. Although education advocates have advocated for changing school education, teaching methods, and teaching practices, implementing CSCL is still challenging [52].

In a computer-supported environment, some practical knowledge is an obstacle to learning. There are also many types of research on CSCL. In the field of computer-supported collaborative learning (CSCL), various methods have been applied to explain when and who is beneficial to collaborative learning and how to improve the design of CSCL, involving the study of the group consciousness of CSCL [53], educational dialogue of CSCL, and so on [54]. CSCL research shows that processing and using information alone cannot result in meaningful learning. To achieve learning, a group needs to establish inter-agent meaning to share and build on each other's ideas [26].

4.2.3. Keyword Analysis

A keyword is a word or phrase in which the author refines the main content of their article. If a keyword continues to appear in the research field, it shows that the word is a hot topic in this research field. Visual analysis and frequency extraction of keywords were carried out using CiteSpace to obtain the research hotspots in this field. The keywords of the WOS core collection were arranged according to the co-citation frequency, and the top 10 keywords are shown in Table 5.

Table 5. The 2012–2022 online collaborative problem-solving top 10 high-frequency keywords.

Ranking	Keywords	Co-Cited Frequency
1	system	49
2	collaborative learning	43
3	online	42
4	student	41
5	model	35
6	education	31
7	collaborative filtering	31
8	framework	29
9	design	25
10	knowledge	25

As can be seen from the table, the top 10 keywords are system, collaborative learning, online, student, model, education, collaborative filtering, framework, design, and knowledge, showing the research hotspots in the field of online collaborative problem-solving.

The system is the environment for online collaborative problem-solving. According to students' learning motivation, learning interest [55], and online learning behavior [56], researchers clarify the connection between students' existing knowledge and resources, establish a personalized online collaborative problem-solving system, and effectively recommend the optimal learning resources for students. To generate high-quality online collaboration, researchers tend to improve online learning platforms.

Collaborative filtering is to filter the obtained information. Students can enjoy rich learning resources with the rapid development of various online learning platforms. However, information overload will hinder students' problem-solving, which requires filtering large amounts of information and ultimately selecting the most favorable resources [57].

The relevant literature was selected for further analysis based on the above keyword analyses' results. Here, it is believed that the research hotspots in the past decade were

mainly focused on the system environment and learning behavior of online collaborative problem-solving.

Construction and selection of an online collaborative problem-solving system. Constructing an online collaborative problem-solving system involves cache optimization and information screening. Many attempts have been made to create and update online systems to reduce the cost of collaborative learning [55]. However, systems that can go beyond the passive accumulation of data often ignore essential variables, such as group size, the difficulty of tasks, and so on [56]. Numerical simulation can explore the complex relationship between these variables and calculate the cost of the online system. Information screening can also effectively reduce the cost of the system.

A collaborative filtering algorithm can be used to establish a personalized resource recommendation model, which is the most mature and popular method. These personalized models can clarify the relationship between students' existing knowledge systems and system resources according to students' learning motivation, learning interest [15], and online learning behavior [58], and effectively recommend the best learning resources for students.

Similarly, research based on learner behavior can lead to the formation of the best online collaborative learning groups. This has been studied to obtain the optimal learning groups that meet different grouping requirements in different educational situations according to the improved genetic algorithm [59]. However, these models need to be further verified in practice. Although the role of students in the process of collaboration forms a robust and stable structure in the space of small group interactions [60], their behavior is constantly changing in the process of solving problems. We need to proceed from the purpose of education, fully consider the characteristics of students, and combine the nature of specific disciplines to constantly optimize the algorithm.

Standard social tools such as MOOC, Facebook, Twitter, and others are widespread in online collaborative problem-solving teaching. Niche platforms include Blogs [61], Skype, and so on. Existing research shows that the learning community of Facebook guides cognition and improves cognitive ability [62]. Twitter is as effective as the instant messaging software Skype in communicating information, and less information exchanged through Twitter will not hurt team performance [63].

Different programs have different characteristics. Educators must choose affordable social media according to their teaching needs and fully consider the potential adverse effects, such as advertising interference, information leakage, etc. [3]. Information security is a risk that needs to be considered in the online education platform. In recent years, there are also some designs to protect users' interests in the research related to the privacy management of online collaborative problem-solving systems. For example, there is a trust-based mechanism that not only protects users' privacy but also encourages users to consider the privacy of others [64]. In fact, in collaborative problem-solving, measuring and protecting the privacy of shared information still needs more research.

Learning behavior in online collaborative problem-solving. Researchers mainly focus on the knowledge construction process in online collaborative problem-solving and consider measuring and evaluating the process. Research shows that integrating collaborative and problem-based learning may optimize students' collaborative and problem-solving skills [65]. Through online collaborative problem-solving, students construct knowledge, find solution strategies, and jointly evaluate solutions in the virtual platform [66].

It is helpful for students to form a deeper understanding of knowledge, understand and master more problem-solving strategies, and improve information literacy to adapt to the development of the times. Online collaborative problem-solving requires the team to reach a consensus, coordinate tasks, negotiate, and monitor how the team works, which are highly related to team efficiency and project quality. These social knowledge-building capabilities can be graded from the initial stage (for example, sharing information) to a more advanced stage (for example, negotiating ideas) [30]. Students exercise their communication and negotiation skills and improve their social skills through collaborative online problem-solving.

As online collaborative problem-solving is a complex skill, it is necessary to establish an effective and reasonable evaluation system. This system includes measuring the solution quality, log file analysis, intermediate results, solution paths, team processes, individual contributions, and the quality and type of collaborative communication [67]. Among them, assessing individual contributions may be more complex, and understanding individual contributions within the group may help explain what is happening. However, analyzing individual contributions in the online collaborative discussion is not comprehensive. Quantitative research on individual contributions mainly focuses on the behavior of participation and interaction [68].

Some studies use the number of individual statements and the length of participation as evaluation criteria [69], which may be a bit one-sided. In addition, cluster analysis combines behavioral and structural information to detect the role of participants in the network. The classification of roles shows varying degrees of recognition and participation [70]. However, the quality of the discussion is ignored. The research shows that by applying the project response theory model, students' behavior in OCPS can be evaluated similarly to traditional test projects [71]. This function of monitoring and evaluation is beneficial to educators' teaching. Previous studies have confirmed the effectiveness of computer measurement [29].

In general, peer-review methods are combined with technology. Some studies have developed a system based on formative peer counseling methods [72]. Both formative and traditional peer counseling methods have significantly improved students' academic performance and reduced their cognitive burden, encouraging mentors and students to become active learners with good learning concepts.

5. Discussion

This study used the CiteSpace visualization tool to explore the research status and hotspots of online collaborative problem-solving in the past decade. The current research situation was reflected by exploring the volume of articles, cited authors, cited journals, co-cited literature, and their distribution. The research hotspots were reflected by keyword analysis, cluster analysis, and keyword emergence analysis.

The number of online collaborative problem-solving posts is on the rise. The number of articles significantly increased after 2015, especially since 2020, which shows that more attention has been paid to this field under the influence of the pandemic. Through the analysis of the cited author, we learned about the authoritative scholars or organizations in online collaborative problem-solving. The OECD has a more substantial influence and has contributed outstandingly to developing this field. Among the cited journals, COMPUTEDUC, COMPUTHUMBEHAV, LECTNOTESCOMPUTSC, and others are more interested in online collaborative problem-solving.

Through the visual analysis of the number of articles issued by the state and institutions, we found that this field's current scientific research forces are mainly distributed in China and the United States. Still, the cooperation between institutions is relatively less. Analysis co-cited through the literature helps to clarify this field's research basis. Among them, the article published by Hesse et al. in 2015, "A framework for teachable collaborative problem-solving skills", had the highest cited volume, and introduced a conceptual framework for collaborative problem-solving, which provided an essential theoretical basis for subsequent research.

The cluster analysis results showed that the top three clusters with larger clustering scales were collaborative, collaborative problem-solving, and computer-supported collaborative learning, which are the main research contents in this field. The research in these three fields reflects the sources and characteristics of online collaborative problem-solving and is closely related to online collaborative problem-solving. Keyword frequency analysis showed that the top ten keywords: system, collaborative learning, online, student, model, education, collaborative filtering, framework, design, and knowledge, defined the research hotspots. According to the analysis and summary, the research hotspot mainly

focuses on the system environment and student behavior of online collaborative problems. Keyword emergence analysis showed that the research hotspot of online collaborative problem-solving in the past three years has mainly been on feature extraction, task analysis, computation modeling, etc.

In general, more and more researchers have begun to pay more attention to online collaborative problem-solving, and the research results are also relatively affluent, focusing on learning strategies, interactions, and students' cognitive or behavioral patterns. Regarding teaching strategies, Lim [73] provides practical guidance for integrating online systems to improve creative problem-solving skills, emphasizing the application of redefining problems, strengthening reflection, and enriching thinking tools and online support systems in the teaching process. In interaction and students' cognitive mode or behavior pattern, Hou [48], through case analysis, found that when learning activities involve role-play activities, the quality of discussion is better, and the solutions are more diverse. However, learners lack in cognitive application, evaluation, and innovation.

Most online collaborative problem-solving is qualitative research, with an empirical analysis of the online collaborative problem-solving process. Case analysis [74], group communication analysis [3], cognitive network analysis [75], social network analysis, and lagged sequence analysis [76] were used to analyze and observe the interaction process from various perspectives [77]. The current effective indicators found include brain–brain synchronization [78], behavioral transition mode [6], and teaching scaffold [79]. Over time, the goal of empirical research has shifted from focusing on factors influencing effectiveness to focusing on how these factors function in the process of mediating interactions. Studies have pointed out that online collaborative problem-solving can effectively improve students' ability to collaborate and solve problems [66], positively impacting students' grades and learning participation levels [80]. Students' problem-solving abilities significantly correlate with their interactions [81]. There are still some problems with online collaborative problem-solving, especially in hardware and software devices.

Regarding hardware, team members must have computers and a good network environment. There is a need for software construction, including interaction, search, and so on. Interaction means that information technology can communicate across time and space, making online collaboration ubiquitous. At present, there are some virtual platforms and chat software that provide interactive functions. Some studies have shown that a series of emotional states experienced in the virtual environment should be similar to those experienced face-to-face [82].

However, the current function of online interaction cannot achieve the effect of face-to-face communication, and creative improvement in communication and interaction is needed. Search behavior is vital to online collaborative learning, including how participants input queries and browse web pages. It is a process in which team members use network resources to acquire knowledge. Complex online search behavior helps to improve the skills of dealing with network information and grasping deep learning methods [83]. It is worth noting that the overload of network resources will also affect students' problem-solving. In collaborative problem-solving, online search behavior and collaborative discussion are closely intertwined. If these two parts can be effectively improved, the effect of online collaborative problem-solving will significantly improve.

There are still some deficiencies in this study. First, the literature of this study is only from the Web of Science database, there was a specific search problem, and we could not exhaust all the research, but as far as possible, we have provided some references for the development of this field in recent years. In addition, the selection strategies of countries, authors, institutions, keywords, and the co-citation literature analysis in this study all select the TOP100, so there may be some restrictions in promoting the research results.

6. Conclusions and Prospect

Online collaborative problem-solving has been regarded as essential and has become the critical content of major international tests. Online collaborative problem-solving activi-

ties depend on the information and communication technology environment. It is a typical form of computer-enabled learning. Online collaborative problem-solving has become an important research direction, and the learning environment, learning behavior, and learning effect are the main research topics. Some countries have carried out a lot of research and produced many results. However, the cooperation between research groups is insufficient and needs strengthening. Based on the above analysis, this study proposes four future directions: identity awareness in online collaborative problem-solving, interdisciplinary online collaborative problem-solving, online collaborative problem-solving for teachers, and online collaborative problem-solving and ICT skills.

6.1. Identity Recognition in Online Collaborative Problem-Solving

The online collaborative problem-solving research analyzes individual behavior and group interaction. The research on individual behavior focuses more on individual cognition, emotion, and behavior patterns, and less on personal identity and role-play. Identity cognition in online collaborative problem-solving reflects the relationship between individual behavior and group interaction and is a potential driving force in knowledge construction. Recent research suggests that participants' diversity awareness may increase the creative potential of the collective sharing of ideas [84]. However, our understanding of the types of roles in online collaborative problem-solving is still limited. Due to the particularity of the online environment and the high complexity of the collaborative problem-solving process, new roles will be observed in different environments. In the future, we can further study whether these roles will evolve and explore their value in knowledge construction.

6.2. Interdisciplinary Online Collaborative Problem-Solving

Online collaborative problem-solving is widely used in mathematics and medicine to solve complex socio-technical problems, such as infant biotechnology identification [85]. The interactivity of the virtual environment allows for interdisciplinary resource flow and collaborative communication. The output of multidisciplinary results is the source of future innovation [86]. The closer the problems in educational practice are to reality, the more comprehensive they will be. Future research must integrate more of various disciplines' nature and innovation-driven strengths and consider interdisciplinary collaborative online problem-solving.

In addition, pedagogy and psychology are the main theoretical perspectives regarding research methods. With the updating and development of equipment, we can consider understanding online collaborative problem-solving in other disciplines in the future, such as physiology and computer science, and the further study of more broad disciplines, such as the multidisciplinary online collaboration of forest biological economy [87], and use a variety of inquiry models to conduct a more comprehensive investigation.

6.3. Teachers' Online Collaborative Problem-Solving

Online collaborative problem-solving is often used as a teaching strategy of online collaborative learning, and the observation objects are mainly students. Under the background that teachers' professional development has become a research hotspot, the synchronous online collaborative development of teachers has received some attention. Studies have been conducted to provide online professional learning for geographically dispersed teachers. An online mathematical inquiry has shown that the nature and quality of mathematical tasks are essential influencing factors [88].

Teachers' online collaborative problem-solving may provide new ideas for teachers to improve their professional literacy and teaching practice ability. Researchers have been paying increasing attention to this direction since 2020. In addition, it is also an important research topic to reflect teachers' views on online collaborative problem-solving teaching from the perspective of teachers and to explore how teachers provide timely and personalized learning interventions. A recent study examined online teacher guidance and

focused on gender differences among teachers [89]. Future research should further discuss various teaching strategies to enhance the effectiveness of online instruction.

6.4. Online Collaborative Problem-Solving and ICT Skills

Previous studies tend to implement and observe collaborative problem-solving in a virtual environment, and information technology supports the collaborative problem-solving process, but this role is not one-way. Considering the positive impact of collaborative learning on computational thinking (algorithmic thinking, critical thinking, and problem-solving) [90], we believe that combining technology and education simultaneously promotes and constrains each other. We look forward to more discussions in the field of online collaborative problem-solving related to the technological environment and ICT skills.

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