Indian Journal of Engineering & Materials Sciences
Vol. 30, June 2023, pp. 460-467
DOI: 10.56042/ijems.v30i3.3672

Analytical Mapping of Materials Science in Quantum Computing using Cite Space

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Received: 10 May 2023; Accepted: 30 May 2023

Quantum computing is a rapidly growing technology that exploits conventional information theory, computer science, and quantum mechanics principles to address complicated computational problems. The recent breakthroughs in information and communication technologies have yielded profound and intriguing insights into quantum computing research. For more advances in quantum computing, researchers are currently concentrating on exploiting material science in this burgeoning research domain to achieve outperform processing power. Henceforth, a scientometric analysis is undertaken to extract the role of material science in quantum computing by analyzing the published academic bibliometric data using CiteSpace. It appraises the research status quo of the field by analyzing yearly publication growth rate, average citation structure analysis, international research collaboration analysis, most cited publication analysis, and keyword co-occurrence network analysis. It deduced that two-qubit gates, quantum entanglement, and spin fluctuation are the research hotspots. Superconducting qubits and spin-orbit coupling are the current most active research areas in material science assisted-quantum computing research. China, the United States, and Japan are mediating in this field. Furthermore, it offers future research directives and significant clues to researchers for the further diffusion of knowledge in the research domain.

Keywords: Quantum Mechanics, Qubit, Scientometric Analysis, Quantum Entanglement, Keyword Co-occurrence Analysis

1 Introduction

The 21st century is an era of interdisciplinary research that will enable human to achieve the tasks which were impossible till now. Amongst these challenging technologies, a critical role would be played by quantum computing.[1] It is an interdisciplinary research field in science and technology. Materials science is among one of the disciplines having a great impact on quantum computing. Various research documents in this field have been published as a result of global recognition and intense interest in quality control. Therefore, a highly pertinent investigation is needed to identify the evolution of path-breaking trajectories for scientific advances. The integration of communication technology and materials science, along with other disciplines has increased the development of highly efficient computing systems. In the last decade, research work in this discipline is going at a very fast pace and attaining new heights. A current key research inclination is concerned with finding an alternative to increase the computation power as well as refining existing ones for quantum computing. The two research areas are similar in terms of their goal, but have different implications on future research. Therefore, a progressively synthesized network of 2290 original research and review articles from the Scopus database is obtained from the infancy stage of the evolution of the domain till 2022. Visualization of the literature offers a timely and flexible approach to track the growth of new evolving developments. Therefore, CiteSpace, a scientific visualization and analysis tool is used to ease the analysis of evolving developments[2,3]. Scientometric is the tool for the quantitative and qualitative examination to reveal the research progress of any discipline.[4,5] The article presents an analysis of the literature published in the discipline of materials science in the domain of quantum computing[6]. It explores the measurable aspects of the data to analyze the progress, impact, and relevance of research.[7] It is a crucial arithmetical and visualization analysis to identify significant research topics.[8,9] The analysis enlightens evolutionary research ideas in the field of materials science. The article offers a thorough and improved grasp of various patterns, research hotspots, subtopics, and other features that will form the basis for future research collaborations and initiatives in the field of quantum computing.

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1.1 Objectives

This paper extensively explores the literature on materials science in quantum computing. The work plays a noteworthy role in the field of materials science by providing indispensable insight into different emerging research developments in the area. It will explore the current scientometric takeaway on materials science's role in quantum computing. The main objectives are

- To analyze the publication growth pattern in materials science in the domain of quantum computing.
- To evaluate the publication citation structure of top contributing nations.
- To explore country collaboration networks and most cited articles of the top ten countries to identify emerging trends and technologies.
- To analyze the top active countries in this domain by burst analysis.
- To identify current research hotspots and research frontiers by performing keyword co-occurrence network analysis.

2 Materials and Methods

This section presents the adopted methods, tools, and searching strategies applied in article. It employs a scientometric approach to assess the development paths and emerging research topics in the knowledge domain. It evaluates and tracks the research performance, scientific growth pattern, and various research dynamics in a specific science and technology discipline. Processing of broader range of data manually is very costly and time-consuming. The advantage of Scopus over other databases is that it collects and processes the database of publications by using analytical tools. It provides a comprehensive assessment of high-quality publications with accurate citation numbers. Scopus exports the data in a structured format and offers information in different formats like abstract, bibliometric information, keywords, citations, and references. Hence, the Scopus database by Elsevier is used in the study.[10,11] Also CiteSpace visualization tool version 6.1. R3 is used for performing country collaboration analysis and keyword co-occurrence analysis to find out various collaborations between different countries[12] and to highlight emerging research trends due to collaboration. CiteSpace offers researchers to identify the scholarly relations among publications and journals. It has compatibility with the Web of Science database. Using its in-built functionality, other data formats can be converted into CiteSpace compatible format. It allows the users to investigate the data in different formats like journals, keywords, authors, sources, countries, and references. The network visualization of scientific literature is represented as nodes and links. The visual attributes of nodes indicate a variety of knowledge about emerging trends, evolution, research hotspots, research fronts, and critical points in the developing field.

2.1 Data Search Strategy

Data is collected from the Scopus database on November 2, 2022. A collection of articles is exported using the keywords "quantum computing" OR "qubit". The query is limited to the title of the article. Further, it is limited to the subject area "material science". Documents are limited to the article and review papers in English language only. The study period is from 1999 to 2022. A total of 2,290 documents are obtained.

3 Results and Discussion

3.1 Publication Growth Analysis

The analysis determines the publication growth in the discipline by analyzing the data in the time slots of three years from 1999 to 2022.[13] The beginning year 1998 is excluded from the study due to a single publication in the year with zero citation count. In the study, the growth rate[2] in the time span 1999-2001 is taken as zero and set as a reference point to calculate the growth of 2002-2004. Figure 1 shows the sharp increase in the number of publications in the beginning time slots from 1999-2001 to 2002-2004. Also, the growth rate is 321.21% which is the highest in the study period. It shows that increase in the number of publications is very high in the initial

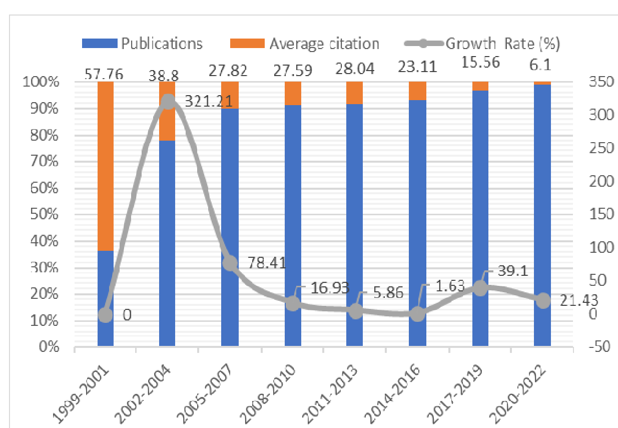

Fig. 1 — Publication Growth Analysis.

periods. There is a significant increase in growth rate from (2014-2016) to (2017-2019) as shown in Fig. 1 which means that significant research work is done in the discipline in this time span. The highest number of publications in the discipline are in the time span of 2020-22 (527), but the growth rate with respect to 2017-19 is only 21.43%. There is a decrease in growth rate despite the increase in the number of publications in the area because, in this time span, other research areas like Covid-19 [(14)] have gained the attention of the researchers. Although, the number of publications is highest in the domain, growth rate is not at the peak.

Also, the data is taken on November 2, 2022, so there is a possibility that the number of publications can still increase till the end of the year and correspondingly, the growth rate will also increase.

3.2 International Collaboration Analysis

This section visualize and analyze the contribution and collaboration between different countries in terms of leading countries contribution analysis.

3.2.1 Top Contributing Countries Analysis

The analysis inclines the contribution of the top ten countries in research in material science in the domain of quantum computing. Table 1 lists the countries which are leading in research in material science and contributed significant publications in the field of quantum computing. It analyses the countries in terms of the number of published articles (P), percentage share of the respective country to the total number of articles (P%), citation count (CC) of the country, average citation rate (ACR) which is the ratio of total citations of the country and the number of publications of the respective country, and RCI (Relative Citation Impact) of the country.[2]

$$\text{RCI} = \frac{\text{Country's Share of Global Citation}}{\text{Country's Share of Global Publications}}$$

A relative citation Index greater than 1 signifies that the citation rate of the country is greater than the world citation rate. It means that the country is contributing high-quality research in comparison to others. The analysis shows that China has published the highest number of research articles 387 with 18.06 percent publication share in total publications in the whole, as shown in Table 1. The United States is in second place with 373 (17.41%) followed by Germany with 148 (6.91%) and Japan with 88 (3.73%). In the CC, the United States is the leading nation, which means that the research work done by this country is finding its place globally. The ACR value of Japan is highest at 35.22, followed by France (27.91) and Canada (27.83). It signifies that these nations are contributing high-quality research papers in the domain. Similarly, the value of RCI determines the influence of a country's research status in global scenarios. In this study, we have found that Japan with an RCI value of 1.58 is the country having the greatest research influence in the domain, followed by France (1.25) and Canada (1.25). The United Kingdom (1.18) and the United States (1.02) are also making their influence on global research.

3.2.2 Network Analysis

The analysis of the network provides important linkage in research work between different countries based on different parameters. It consists 70 nodes, 346 links, and the density is 0.1433. A node signifies a country and links between nodes indicate the connections among countries. A larger node size indicates a larger contribution of the respective country, and the thickness of the link signifies the extent of the connection between countries. Larger is the thickness of link, the greater the research connection between them. "Modularity" (Q) of the network is the extent to which it can be divided into independent blocks, and its value lies between 0 to 1.[(15)] Modularity of the network in the study is 0.259,

Table 1 — Top-10 Most Productive Nations

Country	P	P%	CC	CC%	ACR	RCI
China	387	18.06	4481	9.36	11.58	0.52
United States	373	17.41	8476	17.71	22.72	1.02
Germany	148	6.91	2924	6.11	19.76	0.88
Japan	88	4.11	3099	6.48	35.22	1.58
Russian Federation	80	3.73	677	1.41	8.46	0.38
United Kingdom	68	3.17	1793	3.75	26.37	1.18
India	68	3.17	814	1.70	11.97	0.57
Italy	64	2.99	782	1.63	12.22	0.55
France	58	2.71	1619	3.38	27.91	1.25
Canada	55	2.57	1531	3.20	27.83	1.25

Table 2 — Top-10 Countries by Frequency and Centrality.

Country	Frequency	Centrality	Mean Year
China	387	0.15	2012
United States	373	0.37	2012
Germany	148	0.15	2012
Japan	88	0.08	2012
Russian Federation	80	0.11	2012
United Kingdom	68	0.11	2012
India	68	0.06	2012
Italy	64	0.26	2012
France	58	0.09	2012
Canada	55	0.04	2012

Fig. 2 — Visualization of Country Collaboration Network.

which indicates that clusters are well-defined. The "Silhouette" metric value (S) of any network represents the homogeneity of the network. The range of the silhouette value of any cluster is from -1 to 1.[(16),(17)] The weighted mean silhouette score of 0.714 of the network shows reasonable homogeneity. The values of the network indicate the trustworthiness of the network. As evident from Table 2, much cooperation among countries or regions is observed in the year 2012 (early twenty-first century) as per direct connection among nodes. The top 10 countries that contributed to the total research output are listed in Table 2. China is the largest contributor. Centrality defines the significant influence of a node (country) in the networks.[18] This parameter shows how important a node is, while connecting to other network nodes and thus in maintaining network integration. The purple circumference of the ring on the node characterizes the centrality of that country, as shown in Fig. 2. Thickness of the ring represents the extent of influence of that country. In terms of centrality indicator, the United States is at the top position with a score of 0.37, as listed in Table 2. This means that the United States is playing a significant role while connecting the research work done in different countries in this domain. Italy is in second place with a score of 0.26 followed by China (0.15) and Germany (0.15),

Table 3 — Top 5 Countries by Burst and Sigma

Country	Burst	Sigma
Japan	2.97	1.26
Bahrain	2.16	1.01
Cameroon	1.78	1.01
Argentina	1.75	1.01
Germany	1.6	1.25

indicating their mediating role, distributive and extensive research in the field of quantum computing. Further, it is analyzed that the Russian Federation (0.11) and the United Kingdom (0.11) are actively contributing to the research. France (0.09), Japan (0.08), India (0.06), and Canada (0.04) are emerging countries in the field. Burst is another important analysis parameter which gives the heft of hike for publications with noteworthy change over the specific time period. It represents the rapid surge in the occurrence of publications for the specific time period. Five countries by burst are given in Table 3. Red nodes in Fig. 2 represent the burst of the corresponding country. From Fig. 2, it is clear that Japan, Bahrain, Cameroon, Argentina and Germany are the top 5 countries which have a sudden increase in publication numbers in a specific period of time. Sweden has a red circumference indicating a surge in research publications in recent times. Japan is at the top in terms of burst strength with a burst value of 2.97. Bahrain is in the second position with a burst score of 2.16 followed by Cameroon (1.78). Argentina and Germany are also emerging countries in research publications in material science in the domain of quantum computing. For significant contribution, the value of burst must be greater than 3. It means that all countries are contributing in this domain, but more research contribution is needed. Sigma is an important indicator that signifies novelty in work and must have a value greater than 1 to indicate novelty in work. Japan is at the top position with a value of 1.26, followed by Germany (1.25). Table 4 lists the most cited article in the

Table 4 — Most Cited Article of Top 10 Countries

Country	Citation Count	Year	Author	Title
China	295	2018	Qiang X. et al.(19)	Large-scale silicon quantum photonics implementing arbitrary two-qubit processing
United States	402	2020	Kjaergaard M. et al.(20)	Superconducting Qubits: Current State of Play
Germany	192	2013	Medford J. et al.(21)	Self-Consistent Measurement and State Tomography of an Exchange-Onl Spin Qubit
Japan	586	2014	Veldhorst M. et al.(22)	An addressable quantum dot qubit with fault-tolerant control-fidelity
Russian Federation	69	2021	Pogorelov I et al.(23)	Compact Ion-Trap Quantum Computing Demonstrator
United Kingdom	173	2013	Wolfowicz G et al.(24)	Atomic clock transitions in silicon-base spin qubits
India	54	2015	Choudhury B S and Dhara A(25)	Joint remote state preparation for two-qubit equatorial states
Italy	84	2014	Lo Franco R et al.(26)	Preserving entanglement and nonlocality solid-state qubits by dynamical decoupli
France	314	2014	Nicolas A et al.(27)	A quantum memory for orbital angula momentum photonic qubits
Canada	242	2013	Childress L. and Hanson R.(28)	Diamond NV centers for quantum compu and quantum networks

top ten countries. The top cited article in China is by Qiang X. et al.[19] with a citation count of 295 in the year 2018. In this article, a two-qubit CMOS-compatible quantum processor using silicon photonic structures is realized, enabling optical quantum processing in information technology. The use of silicon photonics for future quantum processors is also highlighted, and a two qubit quantum approximate optimization algorithm is used for the purpose. The review article by Kjaergaard M. et al.[20] in the year 2020 with 402 citations in found superconducting qubits as the top research area because of their utility in the noisy interfering environment. Also, they analyzed the role of superconducting qubits in error correction in quantum computers with high-fidelity. Also, recent experimental developments in hardware and error correction using it are discussed. Medford J. et al.[21] of Germany highlighted Nano electronics role as superconducting qubits and spin qubits. They discussed that addition of third spin provides qubit rotations due to exchange degeneracy, hence full control of spin can be gained through electrostatic gating only. Therefore the three-electron spin exchange qubit performance is characterized in this article by performing measurement and state tomography in the presence interfering environment. Veldhorst M. et al.[22] in 2014 of Japan has number of citations 586 in the discipline. In this article, qubit realization with nitrogen-vacancy centres in silicon (phosphorous and diamond) is discussed. Also a quantum dot qubit with a high control dependability required for fault-tolerant quantum computing is discussed. Pogorelov I et al.[23] with 69 citation count, presented a quantum computing demonstrator on 40 Ca+ optical qubits in a linear Paul trap to address integrated realizations of quantum information processing hardware. Also, measurements related to single-qubit interactions and entanglement are discussed. Wolfowicz G et al.[24] addressed the challenges of decoherence when spins are used for quantum technologies. He showed that atomic clock transition for electron spins in the solid state can be observed particularly in bismuth donors in silicon which increases the electron spin coherence time to a great extent. He found that clock transition-based qubits are less sensitive to an external magnetic field. Choudhury B S and Dhara A[25] proposed an equatorial two-qubit quantum state. They performed unitary operations to achieve the states and showed that the states are successful when parity holding the information transmits it classically to the receiver.

Lo Franco R et al.[26] showed the entanglement preserve and nonlocality of solid-state qubits using decoupling techniques. They investigated the efficiency of an entanglement memory element under two-pulse echo and showed that entanglement and coherence features could be attained for a longer time by using this technique. Nicolas A et al.[27] utilized the orbital angular momentum property of light and the implementation of memory for qubits encoded in the optical degree of freedom is described. Qubits

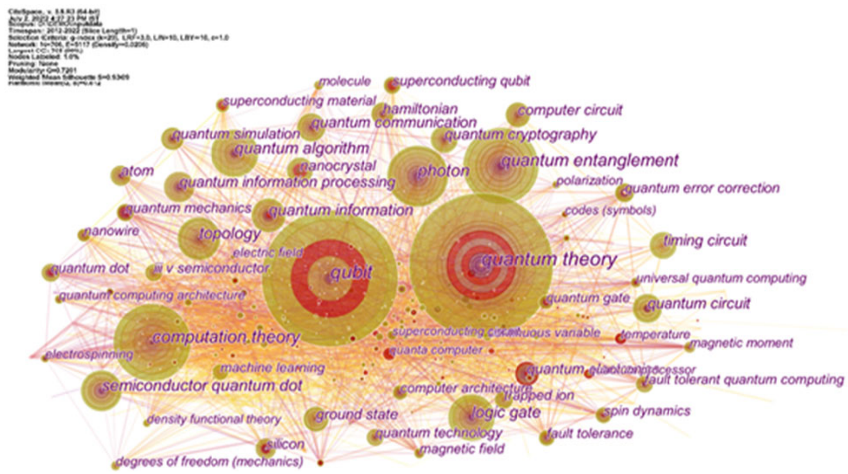

Fig. 3 — Keyword Co-occurrence Analysis of Network.

Table 5 — Top 10 Keywords by Frequency and Centrality

Frequency	Keywords	Centrality	Keywords
649	quantum theory	0.08	semiconductor quantum dot
612	qubit	0.05	defect
362	quantum entanglement	0.04	qubit
294	photon	0.04	photon
207	semiconductor quantum dot	0.04	silicon
130	nanocrystals	0.04	iii-v semiconductor
107	silicon	0.04	nanowire
94	Superconducting qubit	0.03	Quantum entanglement
91	iii-v semiconductor	0.03	Superconducting qubit
65	temperature	0.01	temperature

with computer-controlled holograms are generated, which can be stored and retrieved using an electromagnetically induced transparency protocol. The states are retrieved by tomography and confirm the quantum functioning of the storage process. Childress L. and Hanson R.[28] reviewed the role of nitrogen-vacancy centres in diamonds for finding and controlling a system suitable for non-local correlations to be implemented for quantum processors. Various challenges and future prospects for the use of nitrogen-vacancy centres in quantum processors are also discussed in the article.

3.3 Technological Trend Analysis Using Keyword Co-occurrence

Keywords express the author's academic viewpoints accurately and are the fine-tuning of the main theme of the data. The examination of keywords' co-occurrences can reveal a number of connections between diverse technologies and concepts. Figure 3 represents the analysis of the network. Each circle in the Fig. 3 represents a node corresponding to a keyword or subtopic in the network. The nodes and edges represent the structure of the networks.

The larger the node size, the more frequently the keyword is used in the literature. The network consists of 703 nodes. Different nodes with the same symbolization, such as "superconducting qubits" and "superconducting devices", are recognized and merged as one node. There are 5117 edges in the network. The thickness of each edge reveals how frequently a particular node appears with other related nodes in documents. The network has a density of 0.0206. The silhouette value (S) of this network is 0.9309, and the modularity (Q) is 0.7201. With frequency analysis, the use of promising words, the leading edge and inclinations in the research area can be decided. Frequency is a standard that measure the rank of each node by how often it is used, and it can be used to trace emphases of the field. Frequency of a keyword is the value that tells how frequently it is occurring in the network. The top keyword by frequency is quantum theory with 649 frequency count, as shown in Table 5. The second is qubits with a count of 612. These are the research hotspots in the network. Quantum entanglement and photons are in third and fourth position with frequencies 362 and 294 respectively.

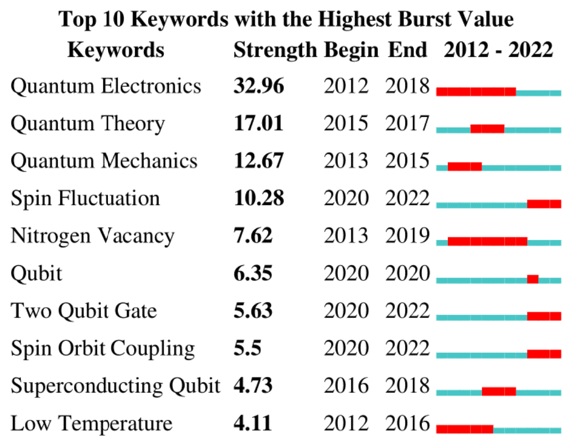

Fig. 4 — Top 10 Keywords with the Highest Burst Value.

Semiconductor quantum dot, nanocrystals, silicon, Superconducting qubit, iii-v semiconductor and temperature are finding their place next with frequency count 207, 130, 107, 94, 91 and 65 respectively. The data shows that these are the main research areas in which work is going on in materials science in the context of quantum computing. In terms of centrality score from Table 5, it is clear that the semiconductor dot is the most influential keyword to make the connection between different research areas, with a centrality value of 0.08. Defects, qubits, photons, silicon, iii-v semiconductor, nanowire, Quantum entanglement, Superconducting qubit and temperature are next to it with centrality score 0.05, 0.04, 0.04, 0.04, 0.04, 0.04, 0.03, 0.03 and 0.01 respectively.

Keywords aid in determining the important research topics in a certain field. The unexpected recognition of a keyword represents that word is repeatedly used in a shorter period and is called burst. These keywords receive special attention from scholars over a certain time. The higher the value of burst strength, the more attention is gained by the keyword. Figure 4 lists the top 10 keywords with the highest burst value. The last column of Fig. 4 denotes the time period for research in the respective keyword. The red line represents the duration of the keyword burst. According to burst strength value, the top-ranked keyword is quantum electronics (32.96), followed by quantum theory (17.01). Occupying the third position is quantum mechanics (12.67), followed by spin fluctuation (10.28). These are the keywords whose burst strength is above 10. Also, spin fluctuation is getting its burst from 2020 till now, as evident from Table 4. It signifies that researchers have been focusing on this research area in recent times. Two qubit gate (5.63) and spin orbit coupling (5.5) are also finding their place from 2020 onwards. Low temperature (4.11) and superconducting qubit (4.73) are attaining the focus of researchers from 2012 to 2016 and 2016 to 2018 respectively because of the interdependence of superconductors on their working temperature. It is observed that quantum electronics, quantum theory, quantum mechanics, spin fluctuation and superconducting qubits are the mainstream trend of quantum computing. However, spin fluctuation, two qubit gate, spin orbit coupling 'have become the research edges in recent years.

4 Conclusion

The application of technology for the betterment of mankind has inspired researchers to put substantial efforts into quantum computing. As a result, the research area attracted global attention and led to a wide research domain in the discipline. The article presented an overall in-depth analysis of publication growth, publication numbers, the geographic distribution of research, citation patterns of publications, and keyword co-occurrence analysis for extracting the collective knowledge pathways of material science in quantum computing research.

It observed that scholarly literature is expanding rapidly owing to the need for emerging technology. The country collaboration analysis of the network revealed that China, the United States, and Germany are the top contributing countries in this research field. Analyses of the top cited article indicated that photonic qubit is among the primary research areas, and silicon photonic qubits are being used in quantum processors to achieve high reliability. Superconducting qubits, another important research area is finding its place in noisy intermediate quantum technology to achieve the entanglement of qubits and their longer coherence time. Moreover, it found that three electron spin qubits also increase the coherence time of qubits because of their lesser sensitivity towards the local external magnetic field. Keyword co-occurrence analysis has revealed that superconducting qubits, photons, iii-v semiconductors and semiconductor quantum dots are the important research areas which are in the centre of the picture and are gaining the attention of the researchers. Spin fluctuation, two qubit gate and spin orbit coupling are the research focuses which are gaining significant attention from researchers in recent times. In all, the scientometric analysis performed in this paper helps a wide array of intellectuals with future research directives and taking informed decisions in this knowledge domain. In response to its future scope, researchers can dig into various research topics by doing journal analysis, author co-citation analysis, and document co-citation analysis. Top contributing institutions can also be highlighted and bring about new facts, innovations and key discoveries contributed by the researchers to keep the scope open and wide.

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