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Article

Visualization and Analysis of Mapping Knowledge Domain of Fluid Flow Related to Microfluidic Chip

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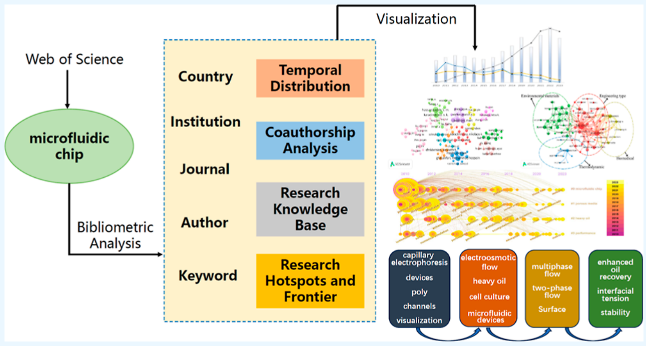
ABSTRACT: Microfluidic chips are important tools to study the microscopic flow of fluid. To better understand the research clues and development trends related to microfluidic chips, a bibliometric analysis of microfluidic chips was conducted based on 1115 paper records retrieved from the Web of Science Core Collection database. CiteSpace and VOSviewer software were used to analyze the distribution of annual paper quantity, country/region distribution, subject distribution, institution distribution, major source journals distribution, highly cited papers, coauthor cooperation relationship, research knowledge domain, research focuses, and research frontiers, and a knowledge domain map was drawn. The results show that the number of papers published on microfluidic chips increased from 2010 to 2023, among which China, the United States, Iran, Canada, and Japan were the most active countries in this field. The United States was the most influential country. Nanoscience, energy, and chemical industry and multidisciplinary materials science were the main fields of microfluidic chip research. *Lab on a Chip*, *Microfluidics and Nanofluidics*, and *Journal of Petroleum Science and Engineering* were the main sources of papers published. The fabrication of chips, as well as their applications in porous media flow and multiphase flow, is the main knowledge domain of microfluidic chips. Micromodeling, fluid displacement, wettability, and multiphase flow are the research focuses in this field currently. The research frontiers in this field are enhanced oil recovery, interfacial tension, and stability.



1. INTRODUCTION

The motion of microscopic fluid refers to the flow behavior of a fluid on the microscopic scale. Microscopic flow of fluid is very important for understanding the basic properties and flow phenomena of a fluid. The basic properties of fluid viscosity, diffusion coefficient, thermal conductivity, fluid stability, heat and mass transfer are closely related to the microscopic flow of fluid.[1] The study of microscopic flow can provide guidance for the engineering applications of fluid. For example, researchers in fluid mechanics can improve the efficiency of fluid delivery and reduce energy loss by designing efficient flow channels.[2−5] In chemical applications, efficient reactors and separators can be designed to improve the reaction rate and separation rate by microscopic fluid research.[6−8] In bioengineering, the characteristics of fluid flowing through microchannels can be used for cell sorting, enrichment, transport, and other operations.[9−12] Therefore, it is of great significance to study the microscopic flow of a fluid.

Microfluidics technology refers to the science and technology involved in systems that use microtubes (tens to hundreds of micrometers in size) to process or manipulate tiny fluids (nanoliters to milliliters in volume). It is a new interdisciplinary subject developed on the basis of microelectronics, micromachinery, bioengineering, and nanotechnology. It focuses on constructing microfluidic channel system to realize various complex microfluidic manipulation functions, rather than reducing the size of the device.[13] Microfluidic chips can integrate the experimental steps needed in biology, chemistry, and physics onto tiny chips. They are composed of microchannel, microvalve, micropump, microsensor, and other components, which can realize the functions of fluid control, mixing, separation, detection, and so on. Microfluidic chips are characterized by miniaturization, integration, and portability. They can be used for complex and high-precision experimental operations in a small space. Microfluidic chips are applied to many fields.[14−16] In the biomedical field, microfluidic chips can be applied to gene sequencing, drug screening, and disease diagnosis.[17−19] They can also be used for chemical reaction, separation and purification and quantitative analysis in chemical analysis.[20−26] In terms of energy geology,

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microfluidic chips have played an important role in oil and gas exploitation, as well as CO_2 geological storage.[27] By observing the flow of oil, coal methane, and fracturing solvent in the fracture channel of the chips, the single and multiphase flow of oil/gas reservoirs can be investigated.[28,29]

Bibliometrics is able to represent the complex knowledge system in the research field through data analysis, information processing, and graphical representation. Among the most widely used and important methods are cluster analysis, cocitation analysis, co-occurrence analysis, etc.[30,31] Bibliometric methods can be used to present and summarize the academic achievements and development of each research field. For example, Yang et al.[32] used the knowledge mapping method to analyze the methodology of emerging technologies in interdisciplinary fields. Wang et al.[33] sorted out the development of China's cross-border e-commerce through bibliometrics. Shao et al.[34] analyzed coal porosity using Citespace and VOSviewer software, and obtained the development dynamics of global research on spontaneous combustion of coal and gas hazards and trends.

The research applications of microfluidic chips are extensive. Researchers are active in this field, and the research frontiers of microfluidic chips have been changing. Therefore, it is necessary to analyze and summarize the knowledge framework, research evolution, frontiers, and focuses in the field of microfluidic chips. However, there is a lack of comprehensive analyses. There are few studies using bibliometrics to sort out the research content related to microfluidic chips. In order to enable researchers to better understand the current research status and the development trend of microfluidic chips, bibliometrics was used in this paper to analyze this research field by drawing knowledge maps.

The research objects are related papers of microfluidic chips in the core database of Web of Science (WOS) in the past 14 years. In this research, bibliometrics and visual analysis were used to analyze relevant papers, and visualization software Citespace and VOSviewer were applied. The spatial and temporal distribution of paper, cocitation relationship of paper, cooperative relationship of authors, cooperative relationship between institutions and journals, and co-occurrence relationship of keywords were studied in this research. The influential papers and basic knowledge of microfluidic chips were identified. The current theoretical research and development processes were analyzed. The research frontiers and development directions were also explored, and the evolutionary path of the field was determined.

2. DATA AND METHODS

2.1. Data Source. At present, there are many platforms for paper retrieval worldwide, such as WOS, Google Scholar, Scopus, CNKI, WILEY, and so on. WOS is the world-famous academic citation search engine, covering the top journals of multiple disciplines and a wide range of papers. It provides detailed citation intelligence, which makes it easy to understand the impact of papers and analyze academic trends and research associations. The paper data extracted from WOS can cover the research in most of the microfluidics fields. From this view, this work retrieved data from the core database of WOS. The retrieval formula was set as Topic (TS) = (micromodel OR micromodel OR micro model OR microchip OR microchip OR micro chip OR microfluidic chip) AND TS = (fluid flow). The retrieval time was set from 2010 to 01-01 to 2023-12-31. It was found that there were few relevant research papers before 2010 after several retrieval attempts. The number of papers began to have a certain scale in 2010 and have analytical value. Therefore, the starting point was set as 2010. 1115 retrieval records were obtained from 210 institutions in 66 countries, including 195 authors and 231 publications. The types of paper are shown in Table 1. There were six types of documents: articles, proceedings, reviews, early access, book chapters, and abstracts. Among them, the proportion of articles was the highest, reaching 85.93%, followed by the proceeding papers and reviews, accounting for 8.30 and 4.55%, respectively. The other two were small and negligible. The total number of publications in Table 1 was greater than that of the articles. It was because that a paper might belong to two types of publication. Therefore, this research focused on the first three types of papers.

Table 1. Paper Types Related to Microfluidic Chips

rank	type of paper	total publication	proportion (%)
1	article	983	85.93
2	proceeding paper	95	8.30
3	review	52	4.55
4	early access	12	1.05
5	book chapters	1	0.085
6	meeting	1	0.085
total		1144	

2.2. Method. In this article, the paper about microfluidic chips was quantitatively and visually analyzed by bibliometrics. Bibliometrics analysis is a scientific method to explore the laws of paper content, quantity and distribution by means of cluster analysis, cooperative network analysis, co-occurrence and cocitation analysis, etc., so as to understand the research status and trend of the field to be studied and predict the future development direction of the field.[35] VOSviewer and CiteSpace are software tools for constructing and visualizing document metrology networks. They can realize the drawing of scientific knowledge graph and show the relationship between structure, evolution, cooperation, and other aspects of knowledge domain. Their outstanding feature is a strong graphical display ability, which is suitable for large-scale data. They were adopted to visualize and analyze the result and output graphs, so that the development process, research focuses, and field frontiers of the field of microfluidics chips could be better understood. The author cooperation network, author cocitation network, country and organization cocitation network, journal cocitation, keyword cocitation, paper cocitation, and other knowledge maps were drawn by VOSviewer. The keyword timeline and time zone map were drawn by CiteSpace. The main research steps and methods are shown in Figure 1.

VOSviewer's clustering is formed by calculating and mapping the similarity matrix. First of all, in order to obtain a similar matrix, it is necessary to process the data and change it into a co-occurrence matrix. Then the co-occurrence matrix is normalized to obtain the similar matrix.[36] VOSviewer normalizes the co-occurrence data by using a similarity measure known as association strength.[37] The similarity s_{ij} between two items i and j is calculated as

$$S_{ij} = \frac{C_{ij}}{w_i w_j} \quad (1)$$

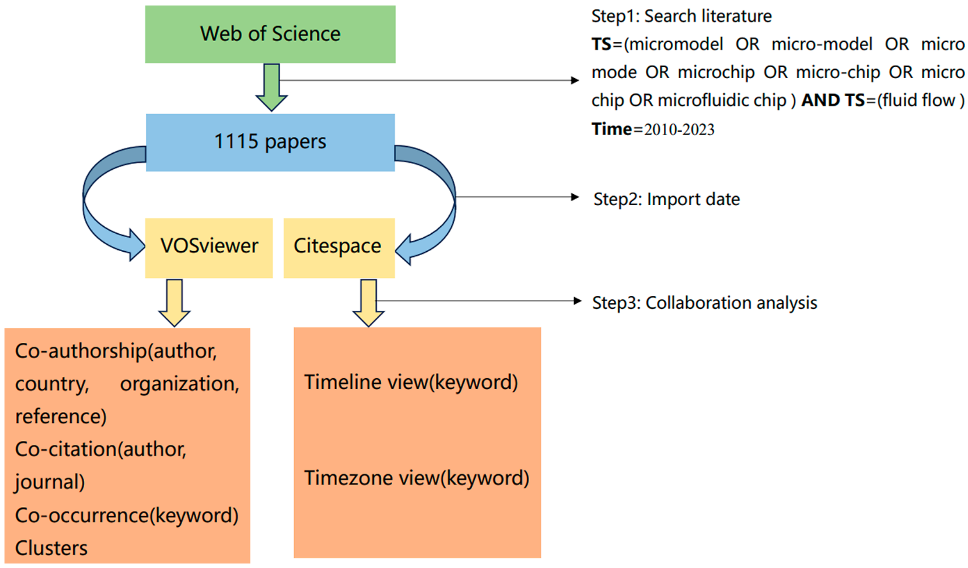

Figure 1. Main research steps and methods.

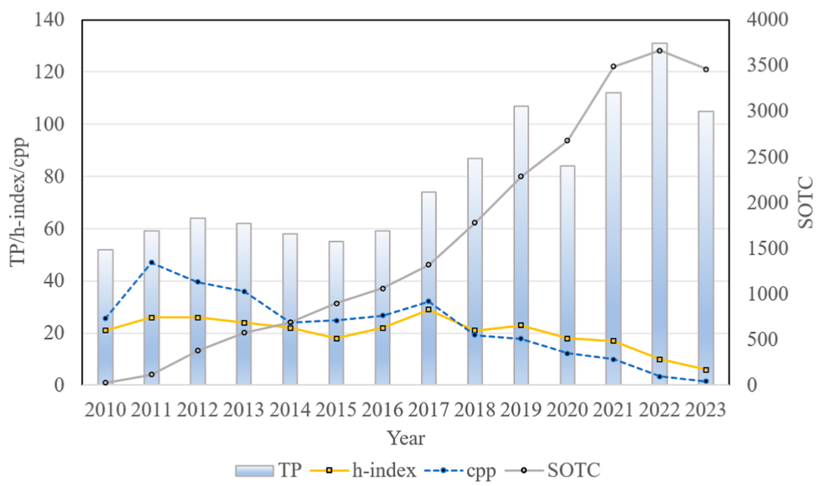

Figure 2. Trend of global publications related to microfluidic chips. (TP: total publications; SOTC: sum of times cited; CPP: citations per paper).

where C_{ij} is the number of co-occurrences of items i and j and w_i and w_j denote either the total number of occurrences of items i and j or the total number of co-occurrences of these items. Second, the similarity matrix is processed by VOS mapping technology, and the cluster is constructed. The specific principles are as follows: the idea of VOS mapping is to perform a distance-weighted sum between all pairs of elements in the minimization. The higher the similarity between two elements, the higher the weight of their distance squared in the sum. In order to avoid the possibility that all elements are in the same location, the constraint that the average distance between two elements must be equal to 1 is imposed. Let n denote the number of elements to be mapped. The elements 1, ...,n are arranged in such a way that the distance between each pair of elements i and j reflects their similarity s_{ij}. Elements with high similarity should be placed close to each other, while elements with low similarity should be placed away from each other. The formula is

$$V(X_1, \cdots, X_n) = \sum_{i<j} S_{ij} \|X_i - X_j\|^2 \tag{2}$$

where the vector $x_i = (x_{i1}, x_{i2})$ is the location of item i in a two-dimensional map and where ‖*‖ is the Euclidean norm. The constraint condition is

$$\frac{2}{n(n-1)} \sum_{i<j} \|X_i - X_j\| = 1 \tag{3}$$

3. RESULTS AND DISCUSSION

3.1. Temporal Distribution of the Papers. *3.1.1. Temporal Distribution of the Papers Globally.* According to the set conditions, 1115 papers related to microfluidic chips were retrieved from the WOS core database. The citation analysis of relevant papers was carried out, and the change of the research on microfluidic chips over time was obtained, as shown in Figure 2. The h-index values here can be exported directly from WOS. The value is intended to show the level of the annual output of paper and the impact of that year. The annual average number of papers published in this field from 2010 to 2023 was 79.64. Through the chart analysis, the trend in microfluidic chip research can be divided into two stages: steady development and rapid growth.

The first stage was stable development (2010–2016), during which the published papers stabilized at about 58 per year. The number of published papers did not increase significantly during this period. A total of 411 papers were published in this field during these seven years, accounting for 35.93% of the total. Most of the published papers used microfluidic chips for porous media and biological cells study.

The second stage is rapid growth (2017–2023), and the number of papers published in this field has increased rapidly since 2017, with an average growth rate of 69.8% higher than that of the first stage. A total of 733 papers were published in 6 years, accounting for 64.07% of the total. In addition, the number of citations also increased significantly and grew rapidly in this stage. In recent years, researchers have invested a lot in the utilization of microfluidic chips in computational fluid dynamics, nanoscale particles, oil, and coal bed gas extraction.[12,38−42]

3.1.2. Temporal Distribution of the Paper by Active Nations. According to the data searched in the WOS core database, it was concluded that five countries, namely, China, the United States, Iran, Canada, and Japan, were currently the most active in the field of microfluidic chip research and had published far more papers than other countries. The development rules of these five active countries were compared by analyzing the time distribution of their published papers, as shown in Figure 3. Before 2017, the research and utilization of microfluidic chips in the United States was at the leading level, and the number of published papers was much higher than that of other countries, and the number of published papers in the United States in this field was relatively stable without great change. With the development of microfluidic chips, China has paid more attention to the research field of microfluidic chips since 2017. The number of publications of China surged in 2017 with further research, thus affecting the growth of global publications in related fields. It was almost equal to the number of United States. China's number in this field had continued to increase since then and increased further in 2021 to become the country with the highest number of publications. From 2021 to 2023, the number of published papers in China continued to increase, while the number of published papers in the other four countries declined year by year. Although Japan, Iran and Canada ranked in the top five in terms of paper publication, they have been at a low level compared with China and the United States, and the number of Iranian papers has increased slightly after 2018, which can be seen as China and the United States being in the core position in the research field of microfluidic chips.

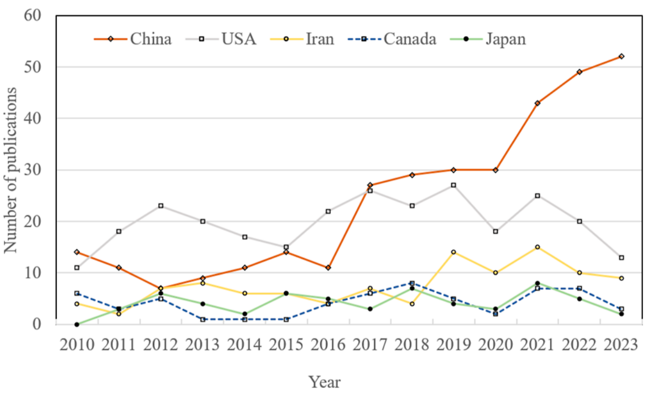

Figure 3. Trends in publication growth for the five active countries (China, USA, Iran, Canada, and Japan).

3.2. Spatial Distribution of the Paper. *3.2.1. Country/Region Distribution.* Data on microfluidic chips in 64 countries and regions were obtained from the WOS database. The top 10 countries and regions with the highest number of published papers were selected for comparative analysis, as shown in Table 2.

In Table 2, the quantity is the total number of papers published in each country. Percentage is the proportion of the total publications. The h-index, which is exported from WOS, represents the influence of papers in the country or region. The ACI is the average number of citations of papers. Total link strength is the total number of co-occurrences of a keyword with other keywords. It indicates the frequency of cooperation between a country and other countries. The number of published papers and h-index were plotted on the world map. Countries are marked in different colors to allow for a more intuitive analysis of the region of the country in which the paper was published, as shown in Figure 4.

As can be seen from Table 2, China and the United States were far ahead in the number of publications in this field and were the two countries with the most. The h-index of the United States was the highest, and the ACI was also at a very high level. It can be seen that the United States had a great influence on microfluidic chip research and was very mature. By contrast, although the number of papers in China was the highest, the ACI ranking was low. The Netherlands had fewer publications and the highest ACI, indicating that research in this field had a huge impact.

Table 2. Top 10 Countries/Region in Microfluidic Chip Research, 2010–2023[a]

rank	country/region	location	quantity	percentage (%)	h-index	ACI	total link strength
1	China	East Asia	338	29.54	34	16.69	109
2	United States	North America	280	24.48	51	30.68	169
3	Iran	West Asia	106	9.23	23	18.68	44
4	Canada	North America	60	5.24	19	20.22	32
5	Japan	East Asia	58	5.07	18	17.76	23
6	Germany	Europe	54	4.72	22	22.48	54
7	South Korea	East Asia	51	4.46	18	26.35	24
8	Netherlands	Europe	49	4.28	22	38.98	46
9	Taiwan, China	East Asia	47	4.12	13	10.74	10
10	England	Europe	46	4.02	21	25.52	54

[a]ACI: Average Citations per Item.

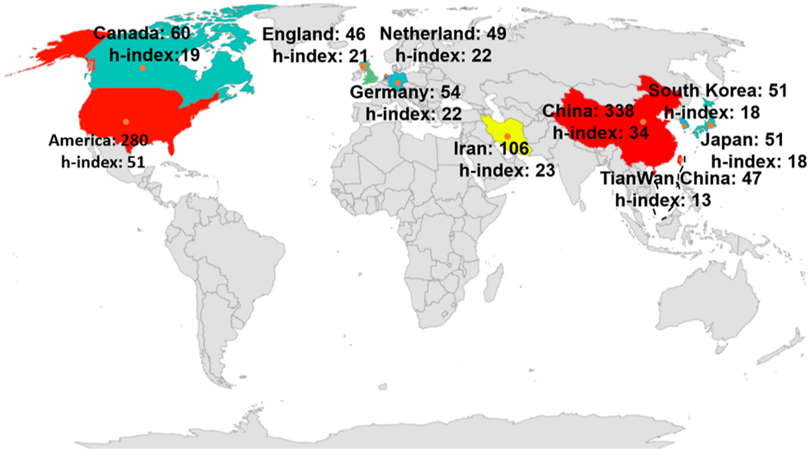

Figure 4. Top 10 countries/region in paper production and h-index.

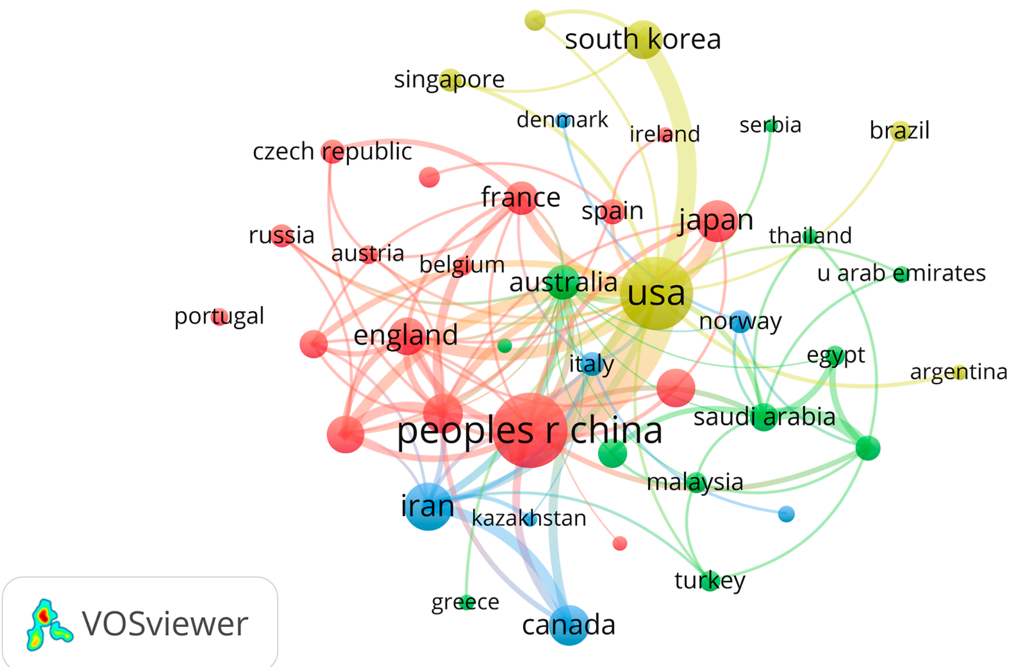

Figure 5. Cooperation among countries and regions in microfluidic chip research.

The 1115 retrieved records were imported into VOSviewer for calculation of total link strength and visualization of national and regional cooperation networks. The results are shown in Table 2 and Figure 5 respectively. In Figure 5, each node represents a country, and the larger the node, the more papers the country has. The width of the connecting lines between nodes indicates the strength of cooperation between countries. The thicker the lines, the closer the cooperation. The United States and China had paid the most attention to the research of microfluidic chips, and they also had the closest cooperation. Although China ranked first in the number of publications, its cooperation intensity with other countries was low. It was one of the reasons for the low ACI value of China. Meanwhile, the focuses of scholars in different countries in this field were also different. The United States and China paid more attention to nanoscience and chemical analysis. Iran and Canada scholars studied energy fuels most. Japanese researchers focused on the field of instrumentation.

3.2.2. Disciplinary Distribution of Paper. By analysis of the subject distribution of the paper, the subject categories in the field of microfluidic chips can be better understood. In this paper, 89 disciplines of different categories were obtained through CiteSpace analysis data, among which 10 disciplines with the largest number of publications are shown in Table 3. Among them, nanoscience nanotechnology was the discipline with the largest number of articles published. There were 266 papers published, accounting for 26.49% of the total. The second and third disciplines in terms of publication volume were chemistry analytical and instrumentation, accounting for 23.71 and 20.42%, respectively. Centrality is a concept used to measure how close a point in a network is to the center of the entire network. It represents the attention degree of the paper, and it is an important index to measure the importance of the paper. Of the top 10 subject categories, the highest centrality was multidisciplinary materials science, at 0.22. Obviously, although the number of publications of this discipline was small, it was a research focus in this field. Next are nanoscience,

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Table 3. Top 10 Subject Categories for Microfluidic Chip Research

rank	quantity	centrality	WOS categories	percentage (%)
1	266	0.21	nanoscience nanotechnology	26.49
2	238	0.13	chemistry analytical	23.71
3	205	0.14	instruments instrumentation	20.42
4	123	0.09	biochemical research methods	12.25
5	121	0.11	chemistry multidisciplinary	12.05
6	120	0.09	physics applied	11.95
7	114	0.14	energy fuels	11.35
8	110	0.15	engineering chemical	10.96
9	87	0.22	materials science multidisciplinary	8.67
10	85	0.01	fluids plasmas	8.47

at 0.21, chemical engineering, at 0.15, energy fuels, at 0.14, and instrumentation, at 0.14.

Because the research of microfluidic chips was mostly in the microscopic field, scholars paid more attention to nanoscience, nanotechnology, and material science. At the same time, it was an important tool in the study of fluid flow in energy and chemical industry, so its centrality in chemical industry, energy, and other fields was also high. Therefore, these were popular subjects in the field of microfluidic chip research.

3.2.3. Institutional Distribution of the Paper. According to the data retrieved from the WOS database, a total of 1196 institutions published papers in the field of microfluidic chips. The top 10 institutions with the highest number of publications from 2010 to 2023 are shown in Table 4, which listed the institution, country, quantity of publications, sum of the times cited, average citations per item, and total link strength. Among the top 10 institutions, three were three from the United States and four from China, indicating that China and the United States were the leaders in this field. Sharif University of Technology (Iran) published the most papers (45), followed by the Chinese Academy of Sciences (38) and national laboratories of the United States Department of Energy (25). The top three institutions with the highest ACI were national laboratories of the United States Department of Energy (64.16), University of California (53.43), and Utrecht University (49.91). Chinese institutions published a lot of papers in microfluidic chip research, but their ACIs were not very high and the number of citations was small. The main reason was that Chinese research on microfluidic chips started late, and the research has not been in-depth. In the past two years, with the development of science and technology in China, scientific research investment has been increasing, and the quantity and quality of China's published papers have been rapidly improved. It is expected that Chinese research institutions will have an increasing influence in this field in the coming years.

VOSviewer was used to screen institutions with no less than five publications. The institutions with fewer than five publications had a total link strength of 0, which was not significant for the analysis. Totally, 102 institutions were obtained for the visualization. Four clusters were drawn by removing clusters with less than seven institutions, as the small cluster with less than seven institutions can be integrated into the large cluster. As can be seen from Figure 6, Sharif University of Technology, Chinese Academy of Sciences, Utrecht University and Tsinghua University had the closest connection and frequent cooperation. The blue cluster was based on two universities, Sharif University of Technology and Tsinghua University. Its main research direction was chemical energy, analyzing the influence of the distribution of aperture cracks on fluids. For example, Mohammadi[43] (2020) studied the pore scale mechanism of drilling fluid induced formation damage to improve reservoir performance during production. The red cluster, with the Chinese Academy of Sciences as its core, focused on microfluidic chip design. Song[44] (2020) designed a reverse microfluidic chip scheme to solve the problem of channel blockage caused by stagnation zones. Ma[45] (2019) developed a novel micropump for pumping fluids in microfluidic chips to increase its resolution and maximum flow rate. The yellow cluster, with Utrecht University as the core, mainly studied the application of microfluidic chips in the direction of water resources. Yin[46] (2019) used fluid volumetric simulation to simulate two-phase flow in porous media of different complexity. The green cluster was centered at the University of California and National Taiwan University, and it was focused on nanoscience and biochemistry. Feng[47] (2012) used flow control of microfluidic chips to denucleate cells, enabling cells to denucleate at high speed and transfer rapidly.

3.2.4. Journal Distribution. Journals are carriers of papers; each journal has its established major inclusion categories, and the papers included in them have a greater correlation with the categories in which the journals are positioned. Therefore, analyzing journals as a feature can capture the distribution characteristics in which microfluidic chip-related papers are located and thus understand the research of microfluidic chips in various fields.

Table 4. Top 10 Institutions in Microfluidic Chip Research[a]

rank	institution	country	quantity	STC	ACI	total link strength
1	Sharif University of Technology	Iran	45	938	20.84	34
2	Chinese Academy of Sciences	China	38	676	17.79	26
3	United States Department of Energy	USA	25	1604	64.16	9
4	China University of Petroleum	China	24	486	20.25	12
5	University of California	USA	23	1229	53.43	4
6	Utrecht University	Netherlands	22	1098	49.91	20
7	National Center for Scientific Research	France	21	276	13.14	5
8	Tsinghua University	China	21	490	23.33	12
9	University of Texas	USA	21	332	15.81	10
10	Petroleum University of Technology	Iran	20	631	31.55	25

[a]ACI: Average Citations per Item. STC: Sum of the Times Cited.

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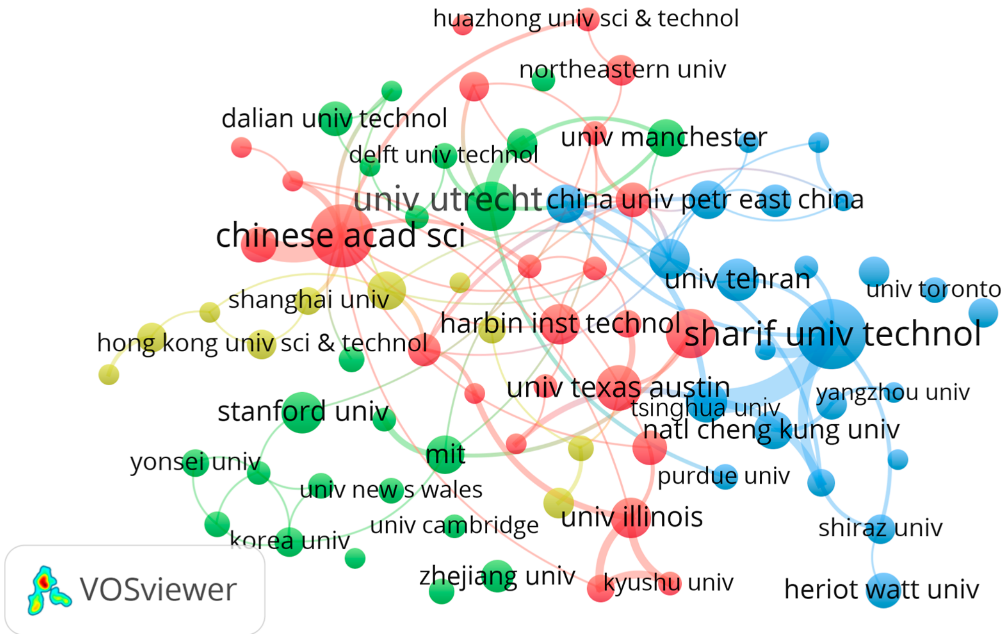

Figure 6. Cooperative institutions in microfluidic chip research.

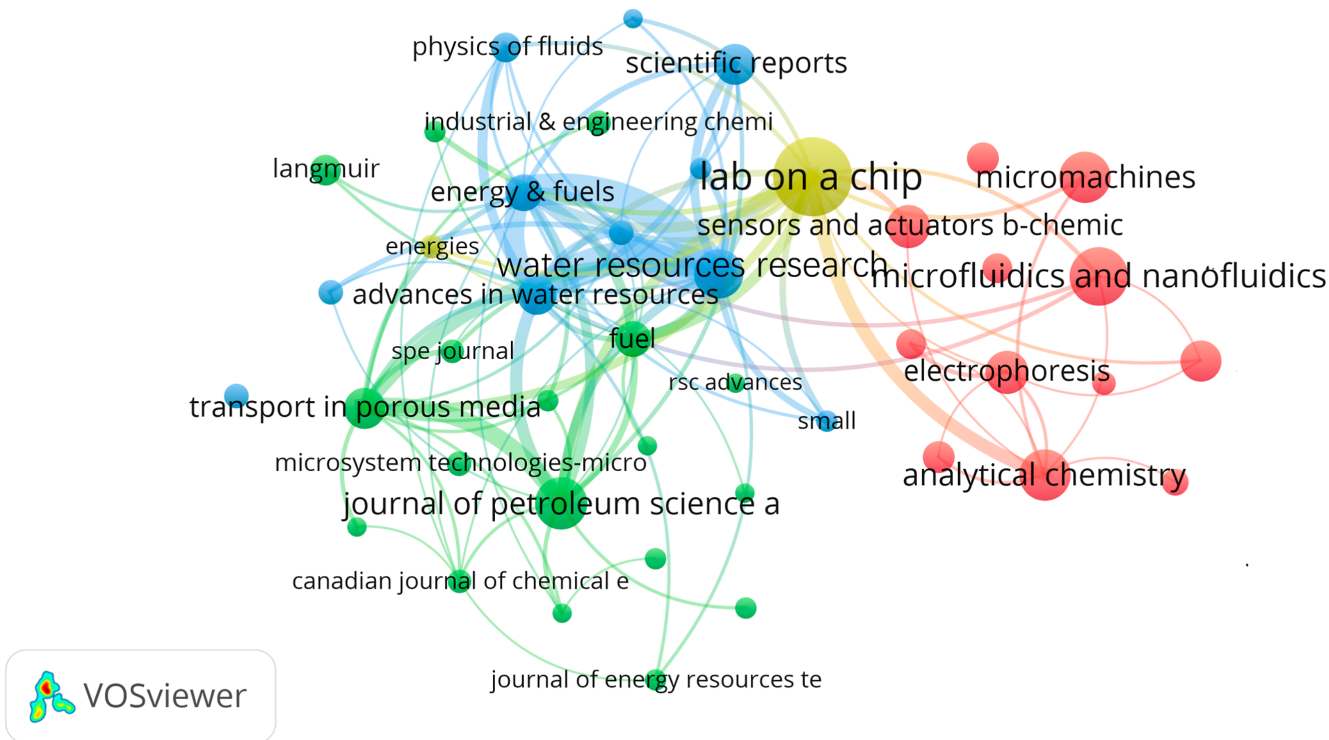

Figure 7. Cooperative main research journals in microfluidic chip research.

Through visual analysis of journals in the field of microfluidic chip research by VOSviewer, a cooperation network of major journals was obtained, as shown in Figure 7. A node represents a journal, and the size of the node indicates the number of papers published by the journal in the field. The larger the node, the more papers published. The thicker the line, the more related the two journals are in the field and the more similar the research content involved. According to the data in Table 5, *Lab on a Chip*, *Microfluidics and Nanofluidics*, and *Journal of Petroleum Science and Engineering* were the three journals with the highest number of published papers.

In this paper, VOSviewer was used to process the paper data in the core database of WOS, and 61 nodes were obtained by excluding noncooperative journals with a total link strength of 0. By using the algorithm of VOSviewer, journals published in similar research fields were clustered to form four clusters. The green and red clusters had the largest number of nodes. The journal with the largest nodes in the red cluster was *Microfluidics and Nanofluidic* and the cluster's core research areas focused on nanomaterials. Journals with large green

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Table 5. Top 10 Journals in Microfluidic Chip Research[a]

rank	journal title	quantity	impact factor (2023)	citation index	ACI	H-index
1	Lab on a Chip	67	6.132	SCI	48.13	30
2	Microfluidics and Nanofluidics	42	2.825	SCIE	14.07	14
3	Journal of Petroleum Science and Engineering	35	4.413	SCI	16.46	16
4	Micromachines	29	3.225	SCI	7.59	8
5	Water Resources Research	29	5.4	SCI	27.66	18
6	Analytical Chemistry	23	7.413	SCI/SCIE	36.7	15
7	Electrophoresis	22	2.915	SCI	13.82	10
8	Scientific Reports	19	4.632	SCI	25.42	13
9	Sensors and Actuators B: Chemical	19	8.409	SCI	15.47	11
10	Advances in Water Resources	18	4.75	SCI	36.56	12

[a]ACI: Average citations per item.

cluster nodes included *Journal of Petroleum Science* and *Engineering and Fuel*, and this cluster focused on petroleum geology. The yellow cluster took *Lab on a Chip* as the core journal, which was related to the design of the microchip's system and also the largest node in the figure. The main journals of the blue cluster were *Energy& Fuel* and *Scientific Reports*. The main research content of this cluster was related to energy as well as clinical sciences. The blue cluster in Figure 7 had more journal collaborations (paper citations) with the green cluster, because the petroleum geology component of the green cluster was more relevant to energy development.

Figure 8 shows the trends of the annual number of publications and the annual average citations of highly productive journals. The peak publication periods of the highly productive journals can be seen in Figure 8a. The main research focuses in the field of microfluidics in each period can be inferred according to the annual number of publications.

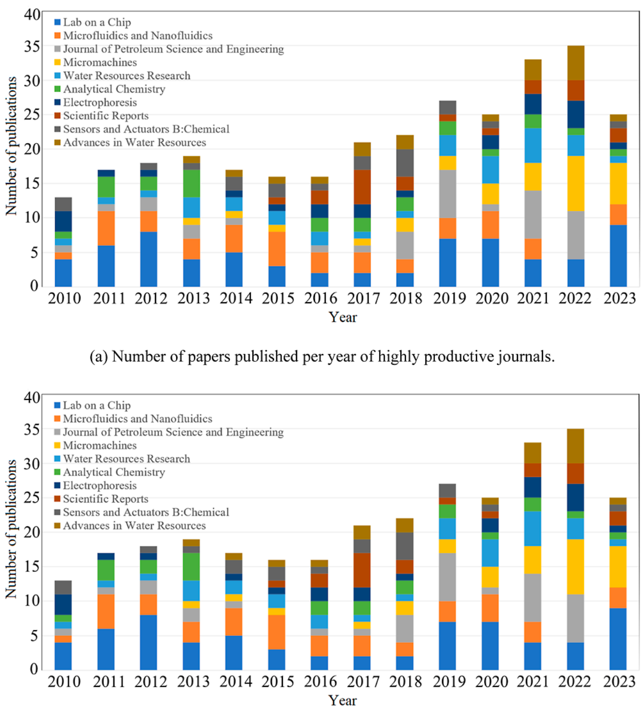

Figure 8. Number of papers published per year and average citations per year of the highly productive journals of microfluidic chip research.

Using the average annual citations of the highly productive journals, readers can understand the overall quality of the papers and the credibility of the research results in each highly productive journal. *Lab on a Chip*'s publications peaked in 2011 and 2017, and geology and biology were focal research field in microfluidic chips in *Lab on a Chip*. Combined with the data in Table 5, the three journals with the higher average number of citations were *Lab on a Chip*, *Analytical Chemistry* and *Advances in Water Resources*, and their impact factors were 6.132, 7.413, and 4.75, respectively.

3.3. Highly Cited Paper Analysis. The number of citations is a direct evaluation of the paper's quality. Through the analysis of highly cited papers, research focus in the field of microfluidic chips can be realized. The top 15 most cited articles in the field are listed, including title, journal, author, type of paper, publication year, etc., are shown in Table 6.

In Table 6, the publication years of the papers with the highest citations are mostly concentrated in the stable development period. Therefore, the previous papers published in this field were of high reference value. Among the 15 most cited papers, most of them were articles and others were reviews. Among them, the review named *Materials for Microfluidic Chip Fabrication* by Ren[53] et al. was the most cited (544), which was published in the journal *Accounts of Chemical Research* in 2013. It introduced the evolution of the materials used to manufacture microfluidic chips, and the advantages and disadvantages of different materials for application were explored. The article *Influence of Viscous and Capillary Forces on Immiscible Fluid Displacement: Pore-Scale Experimental Study in a Water-Wet Micromodel Demonstrating Viscous and Capillary Fingering* by Zhang et al.[54] in the journal *Energy& Fuels* was the second most-cited. The effects of viscous force and capillary force on displacement stability and the fluid saturation distribution of immiscible fluids were introduced. A series of displacement tests in porous media were simulated by using a water-wet microfluidic model. They extended and confirmed the numerical simulation results of immiscible motion in porous media by Lenormand et al.[55] The article named *Optofluidic Fluorescent Imaging Cytometry on a Cell Phone* published by Zhu et al.[56] in 2011 ranked third in terms of citations. This paper emphasized the application of microfluidic chips in the chemical industry and biomedicine. A photofluid imaging cell device was designed by microfluidic channel and mobile phone camera. Through diode excitation light passing through the microfluidic channel, the mobile phone camera could record and analyze the digital frame of the sample to quantify the number of samples. It could be used for various cell counts as well as water quality analysis.

Table 6. Top 15 Most-Cited Articles[a]

rank	title	journal	type	authors	Y	C	NI	NC	Reference
1	Materials for Microfluidic Chip Fabrication	Accounts of Chemical Research	review	Kangning Ren et al.	2013	544	3	1	13
2	Influence of Viscous and Capillary Forces on Immiscible Fluid Displacement: Pore-Scale Experimental Study in a Water-Wet Micromodel Demonstrating Viscous and Capillary Fingering	Energy and Fuels	article	Zhang et al.	2011	305	2	2	22
3	Optofluidic Fluorescent Imaging Cytometry on a Cell Phone	Analytical Chemistry	article	Zhu et al.	2011	302	2	2	56
4	Enhanced cell sorting and manipulation with combined optical tweezer and microfluidic chip technologies	Lab on a Chip	article	Wang et al.	2011	294	4	2	48
5	Acoustofluidics 8: Applications of acoustophoresis in continuous flow microsystems	Lab on a Chip	article	Lenshof et al.	2012	242	2	1	49
6	A Review on efficient thermal management of air- and liquid-cooled data centers: From chip to the cooling system	Applied Energy	review	Khalaj and Halgamuge	2017	240	1	1	50
7	Automated cellular sample preparation using a Centrifuge-on-a-Chip	Lab on a Chip	article	Mach et al.	2011	232	5	2	17
8	Three-dimensional brain-on-a-chip with an interstitial level of flow and its application as an in vitro model of Alzheimer's disease	Lab on a Chip	article	Park et al.	2015	218	4	1	51
9	Lattice-Boltzmann studies of fluid flow in porous media with realistic rock geometries	Computers and Mathematics with Applications	article	Boek and Venturoli	2010	199	2	2	24
10	Paper review of low salinity waterflooding from a length and time scale perspective	Fuel	review	Bartels et al.	2019	193	4	2	18
11	Primary Human Lung Alveolus-on-a-chip Model of Intravascular Thrombosis for Assessment of Therapeutics	Clinical Pharmacology & Therapeutics	article	Jain et al.	2018	185	7	3	15
12	Visualization of improved sweep with foam in heterogeneous porous media using microfluidics	Soft Matter	article	Liontas et al.	2012	173	1	1	52
13	Generation of Gradients on a Microfluidic Device: Toward a High-Throughput Investigation of Spermatozoa Chemotaxis	Plos One	article	Zhang et al.	2015	163	3	1	14
14	Tumour cell identification by means of Raman spectroscopy in combination with optical traps and microfluidic environments	Lab on a Chip	article	Dochow et al.	2011	162	3	1	16
15	A Review of Micromodels and Their Use in Two-Phase Flow Studies	Vadose Zone Journal	review	Karadimitriou and Hassanizadeh	2012	160	1	1	20

[a]Y = Year; C = Citations; NI = Number of Institute(s); NC = Number of Country(ies). (NI and NC are available from the paper information home page in WOS.).

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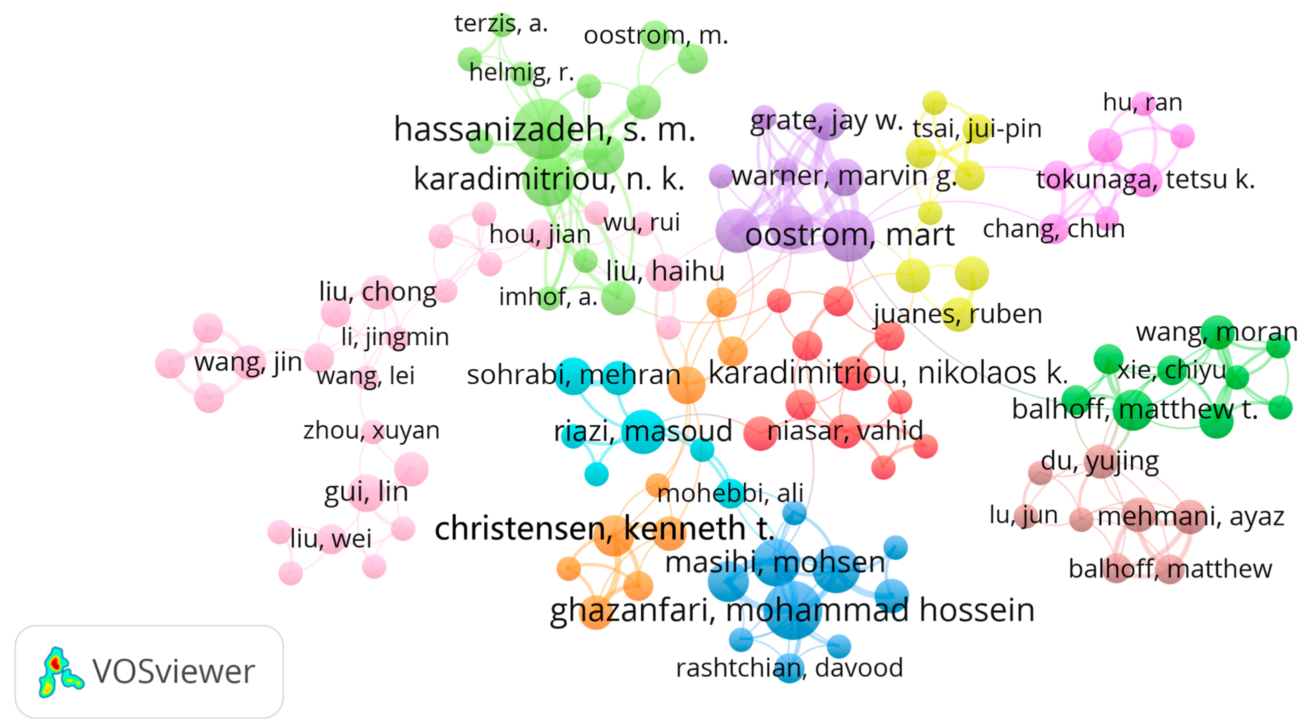

Figure 9. Cooperative authors in microfluidic chip research.

In addition to the top three most cited papers, there were five studies on fluid movement in rock porous media among the other 12 papers. The remaining seven were about human cells, which mainly explored biological mechanisms such as cell enrichment and movement. It can be seen that microfluidic chip models are increasingly being used in studying the motion behavior of fluid in microstructure, as well as in chemistry, biomedicine, and physics.

3.4. Coauthorship Analysis. Coauthor means someone who appears as the author of the same paper. The visual analysis of the coauthor can clearly show the cooperation network of researchers in the field of microfluidic chips, so as to understand the cooperation situation and research direction of scholars in this field. It can provide useful information for comparative analysis of research levels in different countries.

VOSviewer was used to visualize the author cooperation network in the field of microfluidic chip research. The minimum number of published papers by authors was set to 2, forming a total of 11 clusters with 236 authors. The authors with total link strength of 0 were excluded. Further data processing was performed to obtain Figure 9. The size of the nodes represents the number of published documents. The lines represent cooperation between authors. The author nodes in the same cluster indicate that these authors had a common research direction or were conducting the same research together. Nodes in the position of connecting different clusters show that the author had research cooperation among the different fields. The number of connected clusters represents the author's cooperation with other scholars in the field of microfluidics. The authors of different research directions mainly established a common research issue by cross-merging between fields and then integrated their own research methods and techniques to conduct cooperative research.

Figure 9 shows 11 clusters, of which the purple and red clusters are closely related to the other clusters. The node of Mart Oostrom, the node of Mohammad Hossein Ghazanfari, and the node of Nikolaos K. Karadimitriou are the largest. Their works promoted communication and contact among authors of different research directions. Scholars in purple clustering mainly used micromodels to study and analyze fluid flow in pore networks. The light green cluster scholars focused on the study of two-phase or multiphase flow. They used microfluidic chips to explore the colloid transport of two-phase and multiphase flows and the transient-steady state flow properties of two-phase flow. Researchers in the blue cluster focused on simulating the effects of different material pores on the oil recovery rate of mineral deposits and the displacement effect of different solute polymers on heavy oil through micromodels. The scholars of green clustering mainly studied the fluid flow characteristics in the pores of carbonate rocks and analyzed the oil flooding of different chemical polymers under favorable viscosity ratio. The yellow cluster researchers used micromodels to study the effects of liquid wettability on the displacement oil phases. The brown clustering scholars worked on the effect of pore surface roughness on fluids, and mainly studied the pore scale flow dynamics of CO_2 and water through micromodels. The pink clustering included researchers who studied the effects of wettability and heterogeneity on the displacement of immiscible fluids. The scholars of light blue clustering used micromodels to optimize the CO_2 injection formation and storage mechanism. The red clustering focuses on improving the speed and appropriateness of chemical reactions between solvents through micromodels. The specific microchannels were used as a reaction vessel to control reaction rate under different conditions of multicomponent, multiscale, and multiphase states. The light pink clustering scholars mostly applied microfluidic chips in biological studies. The microchannels were used to simulate the xylem channels and stomata of plants to study the water vapor diffusion in plants. In addition, the micromodels were used to grow and enrich cells to simulate the environment in the human body, which is significant for biomedical experiments.

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Table 7. Authors with the Largest Number of Publications in Microfluidic Chip Research in WOS, 2010−2023[a]

rank	author	organization	country	quantities	ACI	links
1	Ghazanfari, Mohammad Hossein	Sharif University of Technology	Iran	22	27.18	16
2	Hassanizadeh, S. Majid	University of Stuttgart	Germany	15	50.73	23
3	Kharrat, Riyaz	University of Leoben	Austria	15	38.87	14
4	Karadimitriou, N. K.	University of Stuttgart	Germany	14	44.5	22
5	Oostrom, Mart	Pacific Northwest National Laboratory	USA	13	81.62	30
6	Masihi, Mohsen	Sharif University of Technology	Iran	11	26.18	14
7	Chen, Xueye	Ludong University	China	11	12.91	2
8	Niasar, Vahid	University of Manchester	UK	10	37.5	5
9	Mohammadi, Saber	Iran University of Medical Sciences	Iran	9	27.44	11
10	Tanaka, Yo	Osaka University	Japan	8	21	5

[a]ACI: Average citations per item.

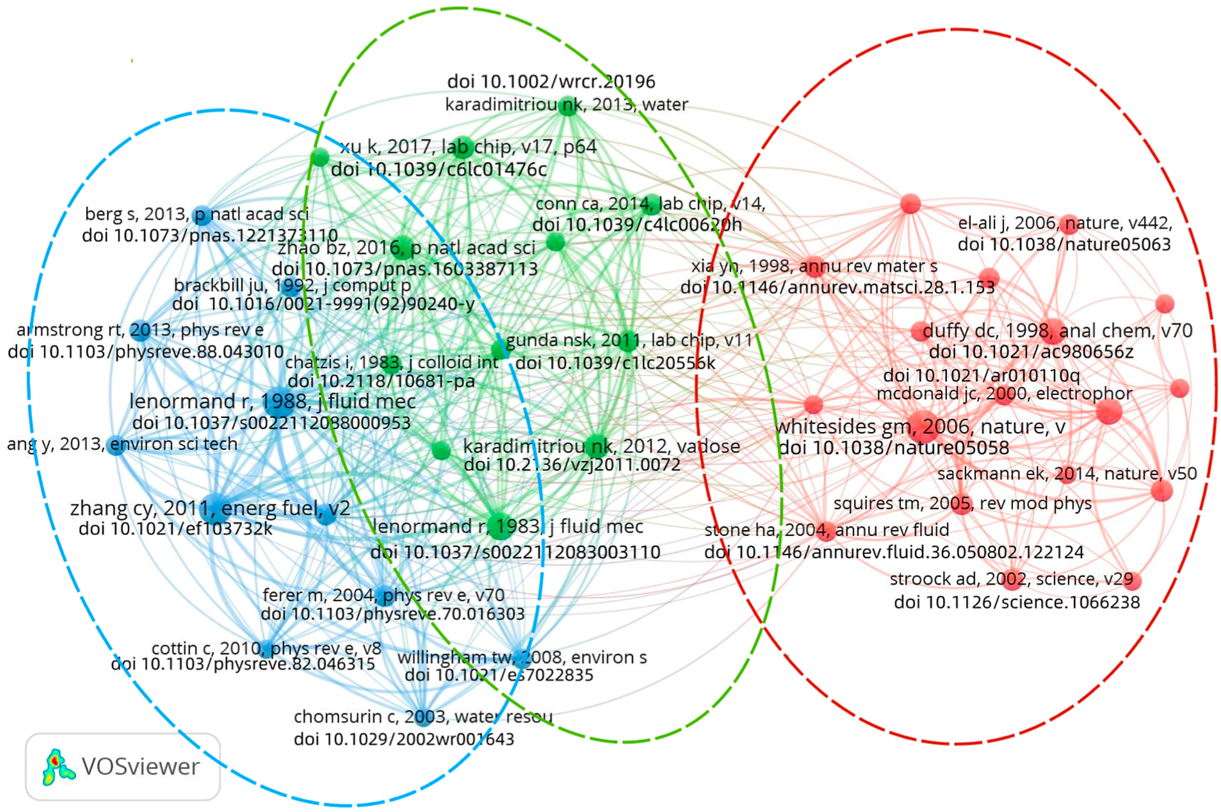

Figure 10. Reference cocitation network of microfluidic chip research.

The information on the top 10 authors with the most publications is shown in Table 7, which included the author's country, organization, average citations per item, and total link strength. As can be seen from Table 7, the highest ACI value was that of Mart Oostrom in the United States (81.62), followed by that of S. Majid Hassanizadeh in Germany (50.73) and N. K. Karadimitriou in Germany (44.5). The United States and Germany had a high level of research in the field of microfluidic chips, and their achievements received a lot of attention. Mohammad Hossein Ghazanfari from Iran published the most papers, but his average citations were at the lower end of the top 10. The number of papers published by Chen Xueye in China was in the middle, but the lowest ACI was his 12.91. Scholars from Iran, China and Japan can cooperate and exchange more with international scholars in the United States and Germany.

3.5. Research Knowledge Domain. Paper cocitation means that two or more papers are cited by other papers at the same time, and then they form a cocitation relationship. The cocited papers have common similarities in the subject matter, so the number of cocitations can represent the relevance of the paper in terms of content. The more the cocitations, the higher the relevance and importance of the paper. These cocited papers constitute the knowledge domain of the research field, and the journals where the cocited papers are located are the carriers of the knowledge domain. In this paper, VOSviewer was used to analyze the cocited papers and source journals to determine the research field of microfluidic chips.

3.5.1. Reference Cocitation Analysis. Cocitation analysis is a bibliometric method used to study the cross-citation relationship between papers. It can reveal which paper has made a significant impact in the academic field.

In Figure 10, VOSviewer was used to perform citation analysis on the selected papers and to process the data to obtain the visual graphics of 43 nodes. The papers with a total link strength of 0 were excluded. The node size represents the

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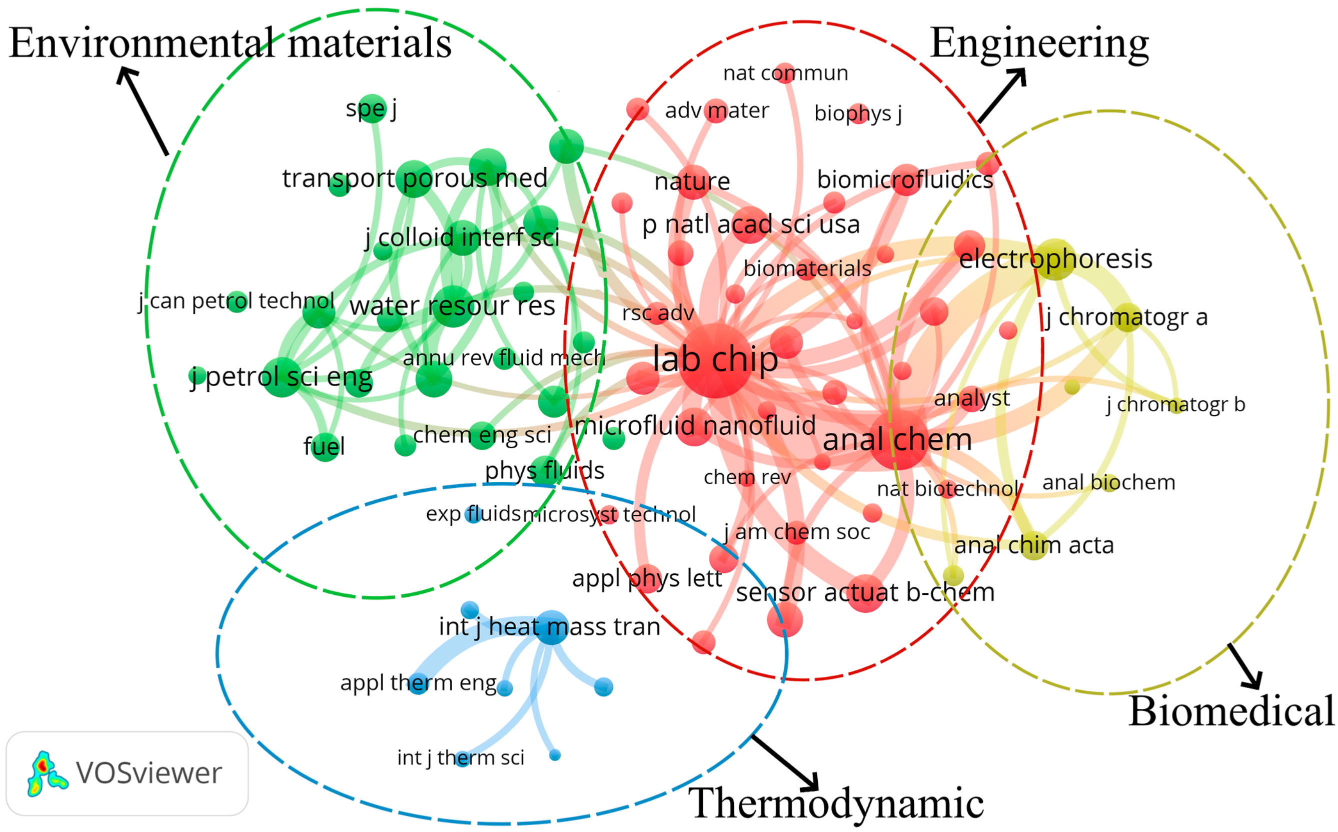

Figure 11. Journal cocitation network of microfluidic chip research.

number of cocitations, and the distance between nodes represents the correlation between the documents. The closer the documents were, the higher the degree of correlation. As can be seen from Figure 10, the paper citation knowledge based on the field of microfluidic chips mainly included three categories:

(i) Application of microfluidic chips in fluid flow of porous media (green clustering). With the development of micromodels, they had been widely used in various fields to study the fluid flow inside microstructures. Through micromodels, researchers observed fluid flow and solute transport in pore spaces, thereby improving the understanding of micro and macro flow phenomena. It has been used in the field of fluid displacement in porous media, fluid−fluid interface area and phase saturation measurement and relative permeability measurement and enhanced oil recovery.[57]

(ii) Two-phase flow analysis (blue clustering). Two-phase immiscible fluid displacement affects geological carbon sink, oil recovery, and groundwater pollution caused by nonaqueous liquids. Microfluidic chips were used to study the two-phase flow and multiphase flow, and analyze the behavior difference of the transmission process, which can characterize the macroscopic flow of the fluid. The study of two-phase flow has also become one of the research bases in this field.

(iii) Microfluidics design (red clustering). The microfluidic chip is characterized by a micropipeline network and contains the fluid at nanometer scale. By designing and adjusting the channel mechanism and size in the microfluidic chip, efficient processing and analysis in various media can be realized. Teh et al.[58] (2329 citations) reviewed droplet microfluidic systems, which have been shown to be compatible with many chemical and biological reagents and can be used for micro-reactions ranging from length scales of nanometers and time scales of femtoseconds, as well as biomedical applications for encapsulating biological entities and exploring pathologic cellular problems.

3.5.2. Journal Cocitation Analysis. At present, the study of multidisciplinary integration is a mainstream. Crossing disciplines can not only broaden the horizon of the discipline but also lead to the forefront of the discipline. By the journal cocitation analysis and the integration of similar journals, the main concentration areas and the core of similar journals can be presented. Meanwhile, this can reflect the interdisciplinary research status of microfluidic chips. VOSviewer was used to take journals with representative disciplines as analysis objects to conduct cocitation analysis of journals. All kinds of miscellaneous journals were integrated and clustered to show their mutual relationships clearly so as to explore the subject structure characteristics of this research field. The visual graph is shown in Figure 11. 249 nodes were obtained through statistical analysis and screening, and these nodes form four clusters. Each node represents a journal, the size of the node represents the number of citations of cocited journals, and the distance between nodes represents the correlation between journals. The closer the distance, the stronger the triggering relationship between journals.

The red cluster represents engineering chemistry journals, mainly included *Lab on a Chip* (3258 citations), *Analytical Chemistry* (1605 citations) and *Proceedings of the National Academy of Sciences of the United States* (560 citations). The yellow cluster was dominated by biomedical journals, with core

Table 8. Top 20 Keywords of Microfluidic Chip Researches

rank	keywords	occurrences	total link strength	rank	keywords	occurrences	total link strength
1	flow	183	884	11	chip	67	314
2	microfluidics	146	646	12	systems	56	313
3	micromodel	83	583	13	phase flow	39	303
4	porous-media	76	505	14	microfluidic chip	90	300
5	displacement	59	432	15	transport	50	299
6	wettability	60	416	16	mechanisms	44	295
7	multiphase flow	57	409	17	model	52	292
8	water	56	369	18	separation	58	274
9	fluid	58	357	19	pore-scale	31	247
10	simulation	53	328	20	visualization	34	241

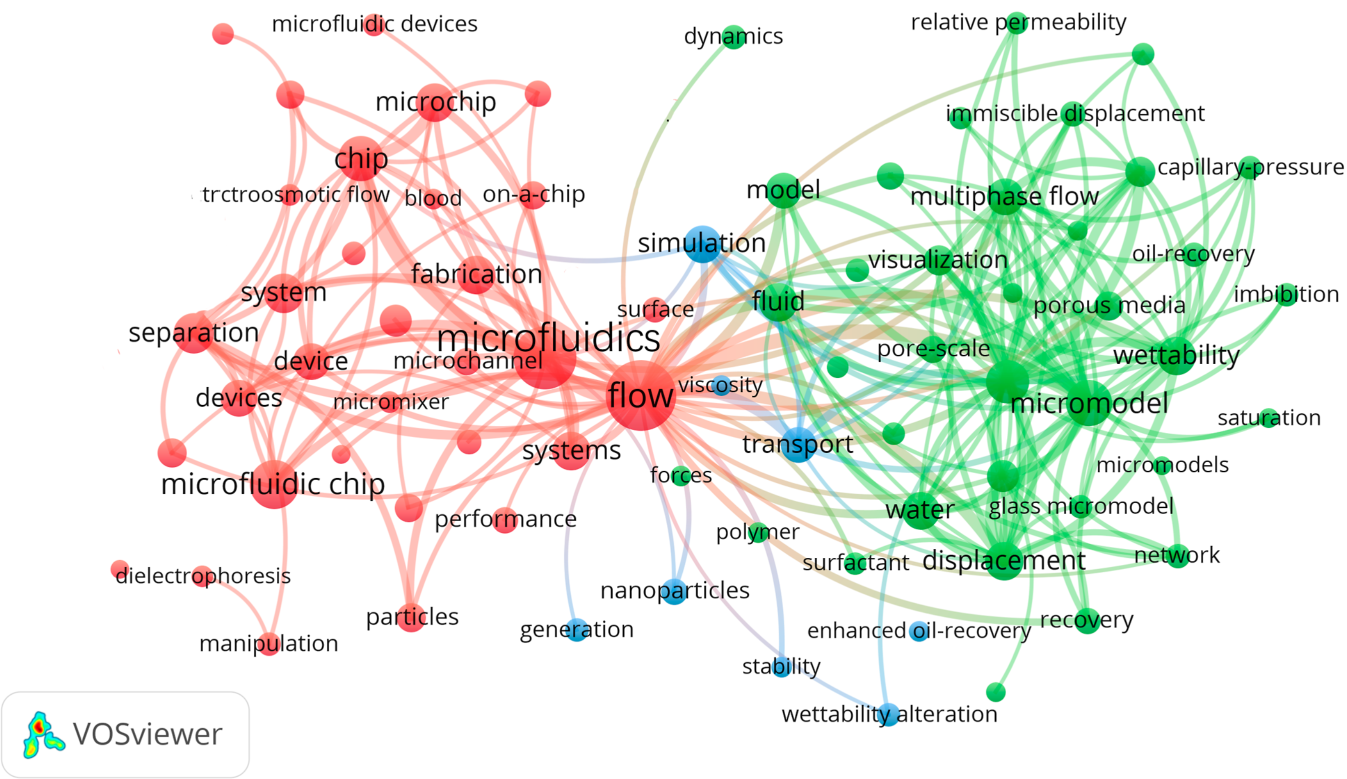

Figure 12. Keyword co-occurrence network of microfluidic chip research.

journals including *Electrophoresis* (622 citations) and *Journal of Chromatography A* (202 citations). The green cluster journals mainly focused on environmental materials, including *Water Research* (792 citations), *Journal of Colloid and Interface Science* (502 citations) and *Energy& Fuel* (410 citations). The Blue Cluster was a thermodynamic Journal with the core of the *International Journal of Heat and Mass Transfer* (395 citations) and *Applied Thermal Engineering* (132 citations). It can be seen from Figure 11 that the red cluster is closely related to the yellow cluster and that the interdisciplinary direction of microfluidic chip research is mainly engineering biology.

3.6. Research Focus and Frontier Analysis. *3.6.1. Research Focus Analysis.* Keywords directly reflect the core content of a paper. VOSviewer and CiteSpace software were used to extract and analyze the keywords of the selected papers, and 4183 keywords were summarized. Through screening, the top 20 keywords with the most frequent occurrences were obtained, as shown in Table 8, which were the most representative pieces of research in this field. Among them, "flow" was the most frequent keyword, appearing 183 times. "Microfluidics" and "micromodel" were the second and third most frequently searched keywords, appearing 146 and 83 times, respectively. The research of these keywords mainly focused on the two-phase flow and multiphase flow displacement of porous media, fluid wetting and nonwetting analysis, and cell biological experiments.

3.6.2. Keyword Cluster Analysis. The keywords were visualized by VOSviewer and formed a keyword co-occurrence network diagram, as shown in Figure 12. The size of nodes represents the frequency of the keyword, and the lines between nodes represent correlations. The width of the line reflects the strength of the connection between them. As can be seen from Figure 12, there were three clusters of green, blue and red in the keyword co-occurrence network, with "micromodel," "transport," and "fluid" as the core keywords, respectively. Among them, the keyword "fluid" appeared the most, and the total connection strength was 884 times. Besides, microfluidic transport in porous media was the main research direction. The popular topics in this field included micromodeling, fluid

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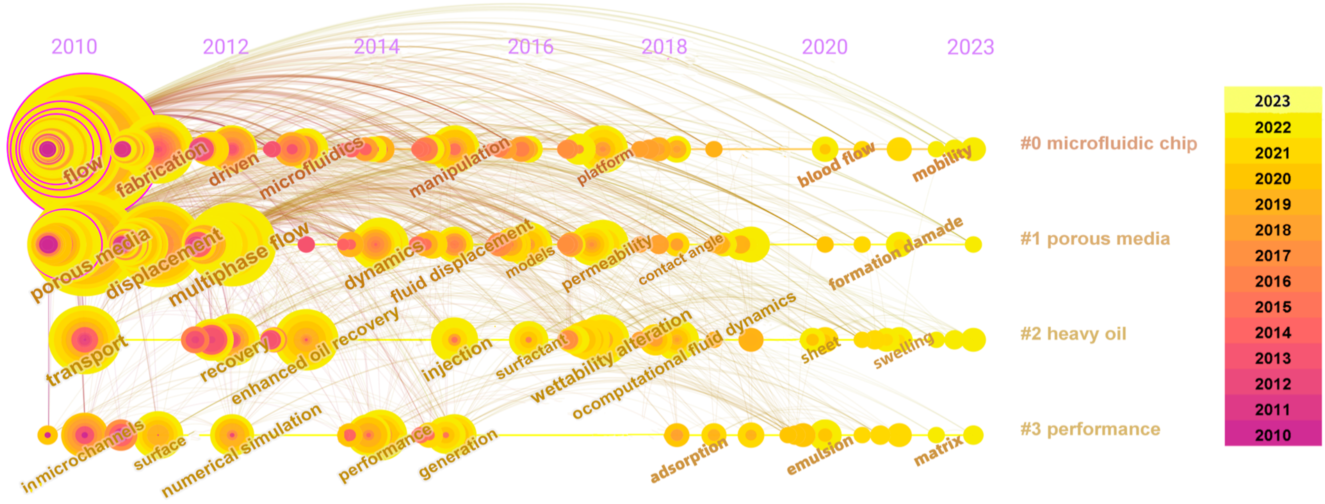

Figure 13. Keywords timeline view in microfluidic chip research.

Table 9. Top 15 Keywords with the Strongest Citation Mutability

Keywords	Strength	Begin (Year)	End (Year)	Period in 2010-2023
capillary electrophoresis	4.76	2010	2013	
devices	4.69	2010	2016	
poly(dimethylsiloxane)	3.8	2010	2013	
channels	3.8	2010	2013	
visualization	3.07	2010	2014	
electroosmotic flow	2.99	2010	2011	
heavy oil	4.58	2012	2014	
cell culture	4.01	2013	2015	
microfluidic devices	4.28	2016	2018	
multiphase flow	4.74	2019	2020	
two-phase flow	3.14	2019	2020	
surface	3.12	2019	2020	
enhanced oil recovery	2.94	2019	2023	
interfacial tension	3.49	2020	2023	
stability	3.1	2020	2023	

displacement, wettability research, and multiphase flow research.

For green clustering, the keyword with the most frequent occurrence was “micromodel” (583 times). The other keywords of this cluster included “wettability,” “displacement,” “porous media,” and “multiphase flow.” This cluster was about the fluids of the porous medium flow in micromodels. The mechanism of macroscopic flow was characterized by the change in multiphase flow in the micromodel. By analyzing the change of its mechanism, the recovery efficiency of oil, coal bed gas, and other geological resources in industry can be improved.

For blue clustering, the cluster mainly revolved around three keywords, “transport,” “stability,, and “viscosity.” In formation, the pores are usually tiny. The capillary phenomenon is an important support for coal bed gas and oil extraction from the formation. At the same time, a stable displacement effect is also the goal of industrial exploitation. The displacement of unstable immiscible fluid affects the recovery rate, and the viscosity is an influence.

For red clustering, the cluster revolved around the keywords “microfluidic,” “flow”, “channel,” “system,” “manufacturing,, and so on. The center word “microfluidic” is typically added to have the paper classified correctly. The focus of the cluster lay in the manufacture and use of microfluidic chip. Microfluidic chips are of high sensitivity, high speed and low cost, and can be used to establish a microenvironment that is easy to control.[59] By manipulating fluids and particles with microfluidic chips, some obstacles at the macroscale can be avoided.[60] The material of the microfluidic chip determines its characteristics and uses, and different materials will have different pertinency. For the first generation of microfluidic manufactured by glass and silicon, it is very suitable for capillary electrophoresis and solvents.[61−63] The elastomer can be used as the production material to culture the cells in the channel and can carry out complex fluid manipulation, which is conducive to the study of biological cells. Microchips made of

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plastic are popular because they are cheap and varied and can provide a choice for many needs. In conclusion, the development of microfluidic chip manufacturing is maturing, and it is becoming more portable, diversified, and low cost.

3.6.3. Combing Evolution Path. CiteSpace was used to cluster the keywords in the paper. These keywords were arranged on the time axis. They are distributed on a time horizontal line, according to the time when the keywords first appeared in 2010−2023, from left to right. The words on the right side are the overall theme of each timeline, as shown in Figure 13. Each node on the timeline represents a keyword, and the size of the node represents the number of occurrences of that keyword. The keyword that appeared the most times was selected as the label at the same node. The color change in each node indicates the time span of the keyword. When the color changes from dark to light, the degree of change is greater, and the time span of the keyword's existence is longer. The connection lines between nodes indicate the strength of the co-occurrence relationship between keywords. If the outer ring of the node is purple, the centrality of the keyword was not less than 0.1, and it was the hub connecting other keywords. The yellow nodes in the figure represent the newly emerged keywords in recent years, representing the new research trend, among which the highest centrality of each keyword was "flow" (0.12).

In the field of microfluidic chips, the largest hub of the keyword was "flow." As can be seen from Figure 13, from 2010 to 2013, the research on microfluidic chips mainly involved the manufacturing of microfluidic chips and the study of materials, fluid displacement in porous media, and fluid transport mechanism. At that time, the disciplines involved in microfluidic chips were not extensive, mostly in physics and chemistry. Since 2013, microfluidic chips have gradually been applied to biological aspects such as cell enrichment and culture, and a variety of microfluidic models have been used to further study fluid wettability changes, two-phase flow, stability, and other issues.

3.6.4. Research Frontier Identification. Keyword mutability refers to the sudden change of keywords over time. In this article, CiteSpace software was used to list the 15 most mutated keywords, as shown in Table 9. It shows the year in which each a keyword appeared, ended, as well as its strength. From Table 9, it can be analyzed that keywords with strong mutability represent the research frontier of the field in each period. By analyzing the results of key word mutation, the research in microfluidic chips is divided into two stages. In the first stage, "fluid," "porous medium," "fluid transport," and "micromodel" were mainly used to study the microscopic mechanism of fluid flow. In the second stage, "two-phase flow," "oil-recovery rate," and "wettability" were the main lines. The research mechanism of micromodel fluids was characterized to the macroscale, so as to improve the recovery rate of industrial oil and coal bed gas resources. From Table 9, "capillary electrophoresis" was of highest mutation intensity (4.76), followed by "multiphase flow" (4.74). Micromodel was a key tool for the study of multiphase fluids.

Microfluidic technology has obvious advantages compared with traditional large-scale reaction technologies such as reaction vessels, test tubes, and Petri dishes. It is becoming popular because of its miniaturization, uniformity, and high stability. Previous research was mostly limited to the physics and chemistry field. Researchers now tend to take advantage of its highly integrated and small size and combine it with other fields (biology, medicine, and engineering) to solve problems. At present, "enhanced oil recovery," "interfacial tension," and "stability" are in a state of mutation. These have become research frontiers in the field of microfluidic chips. Oil has always been an important fossil energy and strategic resource for all countries. It can be predicted that the use of microfluidic chips to improve the oil recovery rate will be a popular topic in the future. The stable displacement of fluids and the influence of interfacial tension changes on microchannel design will be the main research content of scholars. In addition, the design of microchannels and the manufacture of chip materials will be more diverse and operable, and the application will be more and more extensive.

4. CONCLUSION

The research status and main knowledge structure in the field of microfluidic chips were introduced by bibliometrics to help researchers better understand the research knowledge domain and research frontier. VOSviewer and Citespace software were used to analyze the spatial and temporal distribution, paper cocitation, keyword co-occurrence, research focuses, and research frontiers. The main conclusions are as follows.

(i) The number of papers published in the field of microfluidic chips has been increasing rapidly worldwide. As can be seen from the number and distribution of papers, China, the United States, Iran, Canada, and Japan have published the most papers, of which China was the most active country. The papers covered the fields of nanomaterials, energy and chemical engineering, and biochemistry. Sharif University of Technology, Chinese Academy of Sciences, and the United States Department of Energy, which published the most papers, were the most active institutions in the field. From the distribution of journal sources, it can be observed that *Lab on a Chip*, *Microfluidics and Nanofluidics* and *Journal of Petroleum Science and Technology Engineering* were the most published journals in the field, and they were important channels for researchers and institutions to publish papers and exchange academic knowledge.

(ii) The highly cited papers focused on energy, physics, biology, and other disciplines, which could apply microfluidic chip characteristics to solve specific microscopic problems of specific fluids. According to the author collaboration network, there were 4073 relevant authors. The research direction of the cooperative authors is mostly in the field of energy geology, as well as in the field of biology. Nevertheless, most of these authors had no communication and cooperation with each other. Oostrom from the United States and Hassanizadeh from Germany had the highest average number of citations.

(iii) ″Two-phase flow," "microfluidic chip," "application of microfluidic chip in the study of fluid flow in porous media" were the knowledge domain of microfluidic chip related research. The core journals in this field include *Lab on a Chip*, *Analytical Chemistry Electrophoresis*, *Water Research*, *Journal of Colloid and Interface Science*, and *International Journal of Heat and Mass Transfer*. At the same time, "micromodeling," "fluid displacement," "wettability research and multiphase flow research" were also the research focuses in this field. As time

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goes by, the direction of research in this field is also changing, and now the research frontier in the field of microfluidic chips is focused on the aspects of "enhanced oil recovery," "interfacial tension," and "stability."

Fluid flow has always been an important scientific issue in the fields of physics, energy, biology, environment, and so on. Microfluidic chips are widely used in the research of fluid flow at the microscopic scale due to their advantages of miniaturization and diversified design. They provide invaluable insights and technologies applicable to real-world challenges, advancing our understanding of fluid flow in porous material. The knowledge domains obtained from the visual analysis of bibliometrics enable readers to learn about the countries, journals, institutions, and authors that are currently active in the field of microfluidic chip research, as well as the popular directions and the latest results of the research. It is convenient for scholars who do not know the field and those who are ready to know the field to find the key content quickly so that scholars can accelerate the learning of microfluidic chip knowledge field structure. It could be conducive to exploring the new research direction and focus of microfluidic chip and promoting the more in-depth development of the field.

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K.F. contributed to writing—original draft, data curation, and visualization. C.G. and N.L. contributed to writing—review and editing, conception, methodology, and software. X.L. and K.J. contributed to software. Z. W. and C.Z. contributed to data curation, investigation, and visualization.

Notes

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