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Review article

Bibliometric study of plastics microfluidic chip from 1994 to 2022: A review

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A B S T R A C T

Microfluidic tools are widely used in research and manufacturing to manipulate fluids in micrometer channels. These tools are useful for detecting cell cultures, food pathogens, biomedical, energy, and disease. The affordability, versatility, biocompatibility, strength, and transparency of thermoplastics have contributed to its widespread use in the commercialization of microfluidic chips. A bibliometric study of plastic microfluidic chips was conducted using publications from the Scopus database between 1994 and 2022. The study analysed publications based on countries, journals, authorship, and keywords, while VOSviewer software was used for the visualization. Results showed that the United States and China were the most dominant article producers, accounting for almost 50 % of publications. Lab On a Chip was the most active journal, with 22.84 % of its publications involved in microfluidic chips. The network of keywords was coupled and concluded that Polydimethylsiloxane (PDMS), Polymethyl methacrylate (PMMA), Polystyrene (PS), and Cyclic olefin copolymer (COC) benefitted the researchers of microfluidic chips owing to their biocompatibility, durability, optically transparent, and inexpensiveness. By identifying global trends, key materials, and leading contributors in plastic microfluidic chip research, this study offers valuable insights into the most influential countries, leading journals, and primary materials. These insights are instrumental in guiding researchers, manufacturers, and academics in selecting future research directions and better material choices, particularly in the fields of biomedical diagnostics, food safety, and energy solutions.

1. Introduction

Microfluidic devices for micro-scale analysis method have become the most emerged method for branches of science such as cell biology, chemical analysis, and multiphase fluid flow and featured device manipulated [1]. Current microfluidic developments such as sensitivity improvement, smaller weight, compact size, power efficiency, and lower batch manufacturing cost have made the technology very attractive for scientific application [2–4]. Several types of materials are available for microfluidic fabrication, these include glass, silicon, paper, wood, and plastics, with the latest being the most often used, especially thermoplastics owing to their ease

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of fabrication, low-cost, disposability, and recyclability [5].

The fabrication technology is also expanding from lamination [6–8], nanofabrication [9], laser ablation [10–12], molding [13,14], and 3D printing [15–17]. Microfluidic devices could be fabricated using either replication or direct fabrication. Replication method such as micro-molding is the most preferred, although it can be costly due to expensive equipment and also time-consuming during the fabrication process. In this regard, molds or masters of microstructures are fabricated only once, and micro-channelled devices are replicated from the masters [18,19]. Injection molding comprises several steps: the plastic is heated until above glass temperature (Tg), then injected into the mold through the cavity, and the polymer with the mold is cooled down below Tg before being demolded from the equipment [20]. Direct fabrication including Computer Numerical Control (CNC) milling and laser fabrication, in addition to production of a replication mold, would also provide small and complex channels of microfluidic directly on the thermoplastic chips. One of the laser fabrication methods, CO_2, was found effective in providing an engraved channel on a microfluidic chip made from polymethyl methacrylate (PMMA). The channel then needs to be sealed using an elastomer film such as thermoplastic polyurethane (TPU) or polydimethylsiloxane (PDMS) to maintain localized microfluidic flow through the channel [21–23].

However, the commercialization of microfluidic devices remains challenging, and it can be overcome by several efforts such as standardizing the user interface of each device, improving the fabrication pace and cost-effectiveness, and simplifying the control systems [19,24]. Utilization of thermoplastics is one of the attempts to reduce fabrication costs, while also providing strength, broad range of fabrication methods, and biocompatibility for the devices [25,26]. Various microfluidic devices made from thermoplastics were linked to several disciplines including chemistry, biology, medicine, and energy. PMMA, cyclic olefin copolymer (COC), and polycarbonate (PC) were used as microfluidic material for protein analysis, DNA analysis, and cell detection [27,28]. Polyethylene terephthalate (PET) was used as the material for microfluidic using laser CO_2 fabrication [29] hot embossing [30], and had been utilized for pharmaceutical analysis [31] and tumour cells isolation [32]. High-density polyethylene (HDPE) was presented as microfluidic chip for solvents application, while polystyrene (PS) was acknowledged for its low gas permeability, and polyvinyl chloride (PVC) was utilized for biology and biomedical microfluidic reactors [33]. Polypropylene (PP) material has been extensively used for biomedical and biochemical applications with regard to its decent mechanical properties, UV resistance, thermal stability, and solvents compatibility, although the optical transparency is not as clear as elastomer [34,35].

With the extension of microfluidic technologies, and the necessity of rapid fabrication from thermoplastics, the related form of literature has expanded significantly. On account of that, it is essential to investigate the amplification of research linked to the utilization of thermoplastics as microfluidic devices for the past two decades. Bibliometric analysis is an effective tool for any research field to quantify each development and growth pattern of various publications by employing statistical and mathematical methods [36–38]. Bibliometrics provides an analysis tool for literature documents from any databases by quantitatively and qualitatively inspecting the growth and development of a research topic [39]. This technique has been validated in several studies, such as alternative energy research [40,41], public health [36], knowledge base and educational system [42–45], plastics and their valorisations [46–49], and environmental science [50,51].

Therefore, the aim of this study is to qualitatively and quantitatively analyze the trends of thermoplastic microfluidic-related research literature between 1994 and 2022 in developing countries to examine publication characteristics such as countries, journals, and content explorations. Additionally, the potential of thermoplastic microfluidic is identified to elevate the experimental of thermoplastic microfluidic. These objectives aim to bridge the gap in understanding regarding the current development and regional center of microfluidics, thereby providing insights for future collaborations and material selection.

1.1. Summary of previous studies on bibliometric microfluidics

More than two decades ago, microfluidics was considered as a potential way for modern biology to be implemented [52,53]. Nowadays, microfluidics has significantly grown by making valuable contributions, not only to biology, but also to medical, energy, and disease research. Several articles on microfluidic bibliometric analysis have been published in the recent years, demonstrating the bibliometric analysis of microfluidic utilization in various fields. The potential and future developments of early cancer diagnostic by lab-on-chip (LOC) devices were analysed from 301 related articles between 2010 and 2020 to conclude that the fostering collaborations in the future especially in blood or tumour tissues could assist the advancement of knowledge in the field of early cancer diagnostic [54]. Bibliometric analysis of 703 publications from 2005 to 2020 related to microfluidic in food sector was conducted and provided the main focus of the field, which were food safety, quality, processing, preservation, and detection. The authors also identified several challenges and opportunities in food sector microfluidic such as the need for cost-effective and scalable production, standardization, and integration with existing technologies [55]. Lastly, a bibliometric analysis of organ-on-a-chip devices was carried

Table 1
Previous studies on bibliometric of microfluidics.

No.	Title	Reference
1	Bibliometric potential study of early cancer diagnostic by LOC devices	[54]
2	Bibliometric analysis of microfluidic related to food sector	[55]
3	Bibliometric analysis of organ-on-a-chip devices as a mimic of human organ	[37]
4	Patent of (LOC) devices was analysed using bibliometric	[56]
5	The growing of biosensors and point-of-care diagnostics between 2001 and 2013	[57]
6	Bibliometric review of the global research trend in electrochemical microfluidic	[58]

out and generated valuable insights of the device potential as a mimic of human organ for biomedical and drug discovery by simulating organ microenvironments and cell-cell interactions [37].

Recent bibliometric studies on microfluidics are shown in Table 1. The rapid developments of microfluidic device utilization in various fields should be followed by the expansion of the device itself, especially in the fabrication method and material. It was confirmed by several articles on bibliometric microfluidics device such as patents of LOC devices which revealed significant amount of interest in devices research and opportunity for research collaboration between institutes and industry [56], and the growing of LOC publications between 2001 and 2013 with biosensors and point-of-care diagnostics, are among the most prominent research topics [57]. The microfluidic material is also important in the device scheme and would be beneficial to study the past trends and future prospects, especially plastic microfluidic.

2. Material and methods

The Scopus database was utilized owing to its large proportion in Medicine, Engineering, and Chemistry fields which suits the microfluidic topic [59]. The database was searched using the keywords ("microfluidic chip", "lab on a chip" OR "lab-on-a-chip devices"), and documents published between 1994 and 2022 were obtained. To reduce the vagueness of the analysis, specific classifications were employed, including the language of publication (English), the stage of publication (final), and the types of publications (articles, conference papers, and reviews). Out of 16,304 documents related to microfluidic chip, 1608 documents relating to plastic microfluidic were identified by using additional search keywords ("plastic", "thermoplastic" OR "thermoplastics"). To provide a comprehensive overview of the current state and prospects of microfluidic and plastic microfluidic, several review methods were employed, including h-index, CiteScore, SCImago journal rank (SJR), social network analysis, and content analysis.

2.1. H-index, Citescore, and SJR

In 2005, h-index was proposed as the estimation of researcher's or journal's significance and impact based on their cumulative research contributions on the same subject by measuring the productivity of a journal or author, as well as the cited frequency [60]. It would act as decision support for upcoming research in different scientific fields [61]. CiteScore of Elsevier's is the most recent metric and uses a larger database. It was published in 2016 and rivalled other publication measures [62]. CiteScore of a journal is calculated by dividing citations received by documents published in the last 3 years [63]. Another measuring parameter is SCImago journal rank (SJR) which measures the weighted number of given year citations to documents count of 3-year publication window. The uniqueness of SJR is located in its weighing citations: every citation is counted based on the SJR of the journal giving the citation [64]. In this study, the h-index, CiteScore, and SJR of leading journals involved in microfluidic plastics ranked, showed how the journals have contributed to the field of microfluidic plastics.

2.2. Authorship and content analysis

Authors from different countries often conducted joint research in a specific field to enhance the quality and share knowledge between author's institutions. Mapping the relationship between authors consists of connections between authors and their collaboration [65]. Each author carries their keywords in every publication. Moreover, those keywords build connections among them and can be analysed quantitatively to get a better understanding of how a particular scientific area will be developed. The core keywords frequency commonly indicates the core content of the research subject. This study analyses the authors and keywords of publications and outlines the recent trend in microfluidic plastic research areas. The connections between authors, countries, and keywords were plotted using VOSviewer software to visualize the relationship between them.

The documents identified in the bibliometric review, explicitly addressing this scope, were gathered and extracted from the review database. Furthermore, pertinent articles authored by scholars affiliated with the selected school of thought were retrieved from the reference lists of chosen publications. The ultimate scoping review comprises of 44 articles (Fig. 1).

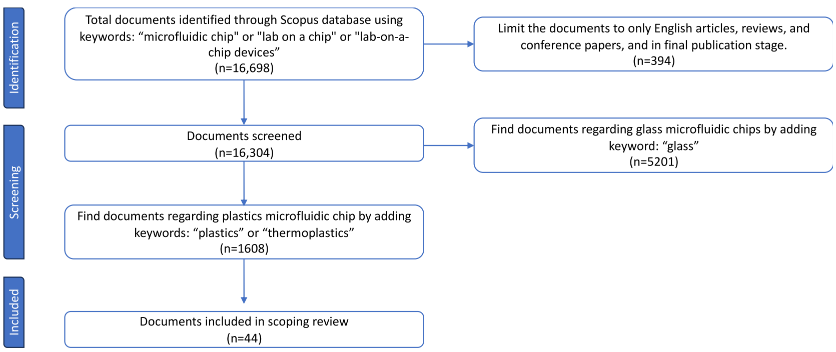

Fig. 1. PRISMA flow chart for bibliometric analysis and scoping review in this study.

3. Results and discussion

This study uncovers the extensiveness of global research on microfluidic devices. From Scopus database search on microfluidic chip, while employing several filters such as journal type, English language, and publication year, about 16,304 documents consisting of 68 % journal articles, 22 % conference papers, and 10 % review articles were acquired.

3.1. Country rank for microfluidic chip

The origin country of each author can be evaluated and provided by addresses and institutions information. Based on the search result of publishing articles in Scopus database, 103 countries have contributed to microfluidic chip research between 1994 and 2022. Although half of the world's countries have contributed to microfluidic chip research, only 20 countries were accountable for 87 % of the total publications. The 20 countries were ranked based on their total publications as shown in Table 2. The United States (US) and China were responsible for almost half of the total publications from the top 20 countries. Indeed, China and the US were leading in terms of microfluidic chip because of infrastructure from their international point-of-care company. European countries such as Switzerland and Sweden were ahead in terms of international collaboration with almost half of their publications being produced in collaboration with other international institutions. The US also ranked high in terms of average citations per article, followed by Sweden and the Netherlands. Countries like Switzerland and Sweden are notable for their high levels of international collaboration, with nearly half of their publications being co-authored with international institutions. There is no significant difference in the average number of authors per article, ranging from 4 to 7 authors per publication. These findings reinforce the position of the current market leaders, all of whom originate from the top ten most productive countries in terms of publication output.

This study also analyses the trend of publication amount for each region: America, Europe, and Asia-Africa. As shown in Fig. 2, in the last 10 years, a decreasing trend in the number of publications from America and Europe has been observed. On the contrary, Asia-Africa had a promising trend from 2012. This positive trend results from research activities going on in China, South Korea, Japan, and Taiwan. These countries have significantly increased their investment in research and development, leading to a surge in high-quality publications. Additionally, collaborative efforts among institutions within these regions have further amplified their research output. Consequently, Asia-Africa is emerging as a new hub of scientific innovation and knowledge production, challenging the traditional dominance of America and Europe in the academic publishing landscape.

3.2. Journal rank for microfluidic chip

Out of the 134 journals that have contributed to research on microfluidic chips, the top 10 journals accounted for 48 % of all publications, indicating their dominance in the field of microfluidics. Table 3 shows the h-index, CiteScore, SJR, and average publications not cited on each subject. There is also a calculation percentage of publication, which is the fraction of microfluidic chip topics in each subject. Lab On a Chip by The Royal Society of Chemistry overtops the ranks with 22.84 % of its publications which deliberated on the microfluidic chip. This is due to the journal's specific scope of micro-technologies. From the h-index scoring perspective, Analytical Chemistry by ACS Publications ranked first. Biosensors and Bioelectronics, with CiteScore of 20.2 and SJR of 2.11, became the highest score in Scopus database due to the low percentage in the average number of publications not cited. The scoring between

Table 2
The 20 most productive countries between 1994 and 2022.

Country	TP	Np (%)	Col (%)	NCI	NA
United States	4661	25.20	11	86	6
China	3246	17.60	10	32	7
Germany	1315	7.10	18	28	7
South Korea	1071	5.80	26	27	6
Japan	1016	5.50	31	19	6
Canada	862	4.70	15	27	5
United Kingdom	850	4.60	30	31	7
Taiwan	645	3.50	15	20	5
Italy	549	3.00	26	26	7
France	540	2.90	14	27	7
Netherlands	516	2.80	30	39	7
Australia	470	2.50	31	32	6
Spain	460	2.50	25	31	7
Switzerland	448	2.40	42	41	7
Singapore	425	2.30	24	34	6
India	358	1.90	28	14	4
Sweden	294	1.60	44	34	7
Iran	254	1.40	35	18	5
Denmark	251	1.40	38	27	6
Hong Kong	234	1.30	55	28	6

TP: the number of total publications; NP: total percentage of publications; Col: total percentage of publications in collaboration with other countries; NCI: average citations per article; NA: average authors per article.

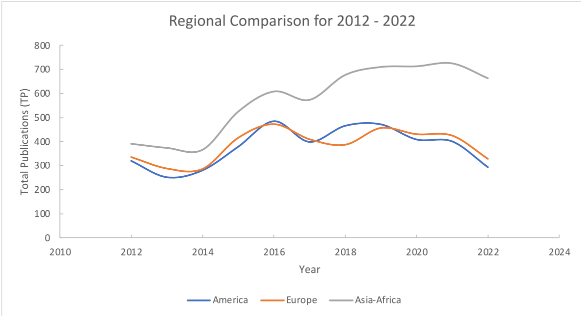

Fig. 2. Regional comparison related to microfluidic publication during 2012–2022.

Table 3
The 10 most productive journals in microfluidic study field.

Journal Name	NP	Total percentage of publications (%)	H-index	CiteScore	SJR	Average of % Not Cited
Lab On A Chip	1804	22.84	221	11.7	1.64	4.01
Biosensors And Bioelectronics	501	3.52	205	20.2	2.11	1.36
Proceedings Of SPIE The International Society For Optical Engineering	384	0.1	179	0.9	0.18	63.21
Biomedical Microdevices	369	19.54	91	6.6	0.57	10.01
Analytical Chemistry	358	0.95	343	11.7	1.79	3.62
Electrophoresis	317	2.75	161	6.3	0.6	9.7
Scientific Reports	314	0.18	242	6.9	1.01	8.43
Sensors And Actuators B Chemical	290	1.03	211	15	1.39	1.85
Micromachines	246	3.33	52	4.5	0.58	8.39
Microfluidics And Nanofluidics	241	9.31	93	5.1	0.48	10.24

NP: number of publications; SJR: SCImago journal rank.

CiteScore and SJR is almost constant because both methods considered the citation count, and not the number of publications. These findings highlight the influence of various countries on the publications, as evidenced by the top 10 journals originating from several nations listed in Table 2, including the United Kingdom, United States, Netherlands, Germany, and Switzerland.

3.3. The trend of glass vs plastic chips in the last ten years

Glass and plastics are regularly used as a substrate of microfluidic chip material due to their good optical clearance and ease of fabrication [66]. Those substrates have been commercially produced as microfluidic chips because the fabrication price is economical. This paper compares the usage of glass and plastic in microfluidic publications from 2012 to 2022 as shown in Fig. 3. The word “glass” was set as the keyword into the Scopus database search engine to filter the microfluidic glass chip publications. Meanwhile, “plastics” or “thermoplastics” were used to refine the database exploration for microfluidic plastic chips. Glass substrate has been the researcher’s preference since the early 2000s with more than 200 publications using glass. However, in recent years, the glass substrate has been less favorable than other inexpensive substrates such as plastic and paper. Thermoplastics utilization trend in the last 10 years is increasing although insignificantly. The use of thermoplastics has broadened to several fields. For instance, development of novel thermoplastic microfluidic bilayer MPS for culturing PHH in a collagen sandwich configuration, which supports hepatocyte functional

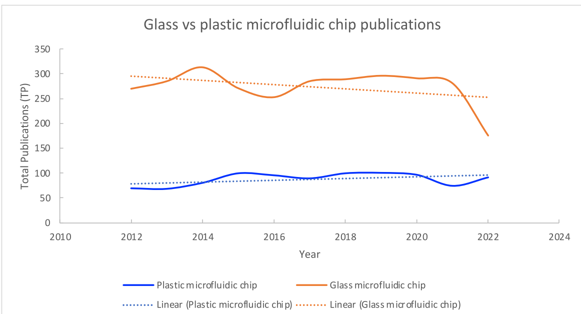

Fig. 3. Comparison of glass vs plastic microfluidic chip between 2012 and 2022.

maintenance and allows the introduction of multiple cellular and media components [67]. Another example is a PMMA microfluidic device capable of withstanding pressures up to 5 tons and temperatures of 100 °C was successfully fabricated for the preparation of liposome particles [68].

Using thermoplastics as a microfluidic chip material offers several advantages. Firstly, thermoplastics are cost-effective, making them a budget-friendly option compared to materials like glass or silicon. They also provide good mechanical stability, which is essential for high-pressure applications. Additionally, thermoplastics provide excellent chemical resistance to organic solvents, acids, and bases, making them suitable for various bioanalytical applications. Another benefit is their low water absorption, which helps maintain the integrity of the microfluidic channels. Many thermoplastics are biocompatible, making them ideal for biomedical applications. Lastly, thermoplastics are easy to fabricate and bond, reducing the complexity and cost of manufacturing. Besides the advantages, there are also disadvantages to using plastics as a microfluidic device. Many plastics are incompatible with a wide range of organic solvents, restricting their use in specific chemical applications.

Some plastics, like PDMS, are gas-permeable, which can be problematic for applications requiring a controlled gas environment. Moreover, plastic materials can be less mechanically stable than glass or silicon, leading to potential deformation under high pressure. The surface properties of plastics can also cause issues with biofouling and non-specific adsorption, affecting the reliability of biological assays. Plastics also have lower thermal stability than other materials, limiting their use in high-temperature applications.

The future of thermoplastic microfluidic devices looks promising due to several advancements. Rapid prototyping techniques, such as 3D printing and laser ablation, are making it easier and more cost-effective to produce these devices [69]. This is accelerating their transition from research labs to scalable manufacturing and product deployment [70]. Additionally, improvements in material properties are enhancing their chemical resistance and mechanical stability, broadening their application range [71]. Overall, these developments are paving the way for thermoplastic microfluidic devices to play a significant role in fields like diagnostics, drug development, and environmental monitoring. By all means, thermoplastics will still be attractive for microfluidic chips in the few years ahead.

3.4. Plastic microfluidic chips

Adding "thermoplastics" or "plastics" keywords into previous microfluidic chip Scopus database advanced search engine yields 1608 documents from 1994 to 2022 with composition as follows: 1078 are articles, 467 are conference papers, and 63 are reviews. This study shows the connections between authors, countries, and keywords from the search result and generates visualization mapping using VOSviewer software.

3.4.1. Bibliometric mapping of countries and authors rank

A total of 57 countries contributed to the subject of plastic microfluidic chips according to the 1608 documents. The cooperation among 57 countries is defined by the connection network diagram shown in Fig. 4. Of the 57 countries, there are 24 countries from Europe, 19 countries from Asia, 2 countries from Oceania, 6 countries from Africa, and 6 countries from America. There are 4 clusters divided by colours: yellow with Germany as the center, green with equal center at Europe countries, blue with Japan as the center, and red with the US as the center. It is essential to observe that China is in the second place regarding total publications but has a wide gap of three times less compared to the US. However, China links the collaboration between the US with the rest of the world.

The US also became the center of research in plastic microfluidic chips, and widen its influence on countries in America, Europe, and Asia. China also built a good connection with Hongkong, Canada, Saudi Arabia, and Turkey. The link between US and China is very notable, as well as the US with Canada, South Korea, and Japan. This is why the United States has an incomparable publication amount compared with the rest of the world. Hence, powerful international collaboration plays a vital role in producing frequent and high-standard publications in microfluidic plastic.

Interestingly, the most cited article is from the United Kingdom, which is on Polydimethylsiloxane (PDMS) characterization and utilization in microfluidic applications and was cited ~981 times [72], followed by collaborative research between Germany and US reviewing silicon membranes for microfluidic technology and cited ~649 times [73]. Other articles which originated from US with ~500 citations are a review article regarding the usage and comparison of PDMS and PS as microfluidic material [74], and a review on design assembly, mechanical and fluidic behavior of 3D-printed microfluidics [75]. The last article which was cited more than 500 times originated from Hongkong, and it focussed on materials for microfluidic chip fabrication [76]. Hence, review articles regarding microfluidic chip material remain the most highly anticipated publications among researchers. Furthermore, the technical aspects of

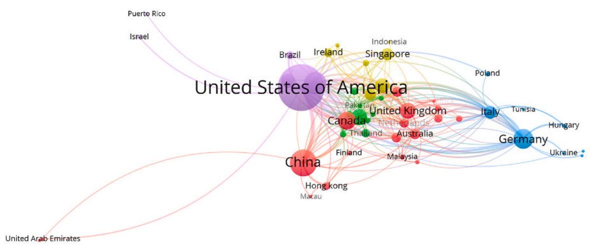

Fig. 4. Collaboration network of 57 countries.

microfluidic research typically commence with a review. An increase in reviews on microfluidics could significantly stimulate extensive technical research into microfluidic techniques and materials.

By using Scopus database, it is possible to investigate the influence of co-authorship. Table 4 shows five authors or co-authors with the most publications and citations. Fan Z.H. leads the group with 23 publications in plastic microfluidics. The most cited publication integrates polymerase chain reaction, valving, and electrophoresis in a single plastic microfluidic device to detect *Escherichia coli* 0157 and *Salmonella typhimurium* bacteria [77]. Veres T. follows closely with 22 publications, with the most cited work investigating the surface modification of PMMA for plastic biochips, which has garnered 103 citations [78]. DeVoe D.L. has 21 publications in the field, and his most cited publication on the bonding technique of thermoplastic microfluidics has received an impressive 493 citations, indicating that his research on the bonding of thermoplastic polymers has had a substantial impact on the field of microfluidics [79].

Ahn, C.H. has contributed 16 publications to the field, and his most cited work, with 473 citations, is the fabrication of a disposable smart lab on a chip that has been tested successfully for lactate level, oxygen concentration, and glucose level in human blood [80]. There are 13 publications in the field of plastic microfluidics attributed to Jeon, N.L. The publication that has garnered the most attention investigates tumor angiogenesis by using a microfluidic platform made from PDMS and PS, and it has been referenced 119 times [81].

In summary, these five authors have made substantial contributions to the field of plastic microfluidics, each with their unique focus areas and impactful publications. This data is crucial in understanding the progression and impact of research in the field of plastic microfluidics.

3.4.2. Bibliometric mapping of keywords

From the plastic microfluidic chip search in the Scopus database, by employing 5 times minimum keyword occurrence, a total of 122 keywords were gathered and plotted to VOSviewer. The author keywords could explain further the main issues of an article and can be useful for future research direction [82]. The mapping of author keywords is shown in Fig. 5. The words “microfluidic”, “microfluidics”, “microfluidic device”, “microfluidic devices”, “lab-on-a-chip”, and “microfluidic chip” have the same implication which states the device of microfluidic. In the mapping, we can conclude that the “device-related” keywords act as the center of the connection. From the center of the connection, which is the device itself, spread the connections to another focus area. The fabrication topic is the closest connection to microfluidic device, represented by fabrication method keywords such as “hot embossing”, “injection molding”, “microfabrication”, “bonding”, “thermal bonding”, and “rapid prototyping”. Microfabrication has the highest total link strength with a score of 54. Microfabrication is the method of fabricating a device in micro-scale, and consists of several techniques such as injection molding, bonding, and hot embossing. Hot embossing has the highest score of link strength among other micro-fabrication techniques with a score of 42. In the microfluidic device field, hot embossing has been used as a micro-channel fabrication on raw thermoplastics. Meanwhile, injection molding has the second highest total link strength with a score of 33. This method uses a mold to form a microchannel device made of thermoplastics. It is worth noting that 3D printing fabrication method has only 17 link strength, but it is no doubt that this method is one of the emerging techniques owing to the rapid development of printing technology.

The second outer connection of the microfluidic device from the keywords mapping is the fabrication material. There are “plastics”, “polymers”, “PDMS”, “cyclic olefin copolymer”, and “PMMA”. Not only is PDMS the most applicable substrate to seal the microfluidic channel on the device, but also it can be formed effortlessly using a mold [72]. PMMA became the highest link strength between microfluidic device materials, with a score of 31. It is the most preferred microfluidic material due to its recyclability, ease of fabrication, high optical transmissivity, high-temperature limitation, and biocompatibility [83]. High optical transmissivity is the primary advantage of plastics and is relevant with the most cited plastic microfluidic device investigating the autofluorescence of PMMA, COC, PS, PDMS [84]. Polymers such as PDMS and PMMA are biocompatible, which make the most outer of bibliometric mapping consists of microfluidic biological-related applications such as “immunoassay”, “pcr”, “biosensors”, “cell culture”, and “bacteria”. It is also shown on the Scopus database, whereas the most cited publication in PMMA microfluidic devices are related to cell tissue, DNA separation and detection [85,86].

3.5. Discussion

The analysis of the origin country of each author reveals a significant concentration of research in the field of microfluidic chips. Although contributions have been made by 103 countries between 1994 and 2022, it is noteworthy that 87 % of the total publications

Table 4
The 5 authors/co-authors with the most cited article in the plastic microfluidic study field.

Author/co-author	Publications in plastic microfluidic	Most cited publication	Citations
Fan, Z.H.	23	Integrating Polymerase Chain Reaction, Valving, and Electrophoresis in a Plastic Device for Bacterial Detection [77]	182
Veres, T.	22	Surface modification of thermoplastics - towards the plastic biochip for high throughput screening devices [78]	103
DeVoe, D.L.	21	Bonding of thermoplastic polymer microfluidics [79]	493
Ahn, C.H.	16	Disposable Smart Lab on a Chip for Point-of-Care Clinical Diagnostics [80]	473
Jeon, N.L.	13	Tumor spheroid-on-a-chip: a standardized microfluidic culture platform for investigating tumor angiogenesis [81]	119

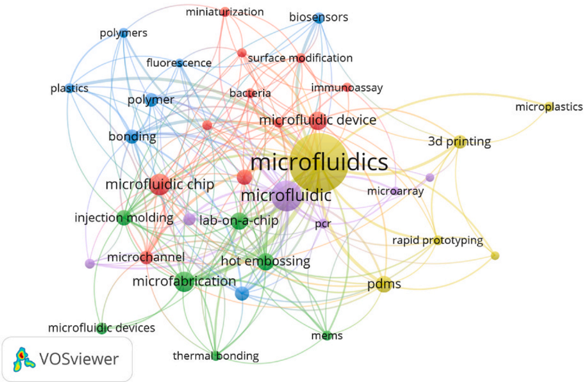

Fig. 5. Network visualization of 122 keywords related to plastic microfluidic chip.

are accounted for by only 20 countries. The United States and China are at the forefront, responsible for almost half of the total publications from these top 20 countries. This dominance can be attributed to the robust infrastructure provided by their international point-of-care companies. European countries, particularly Switzerland and Sweden, lead in terms of international collaboration, with nearly half of their publications produced in partnership with other international institutions. In terms of average citations per article, the United States ranks high, followed by Sweden and the Netherlands. The average number of authors per article does not show a significant difference, ranging from 4 to 7 authors per publication.

A regional analysis of the publication trends over the last decade reveals a decreasing trend in the number of publications from America and Europe. In contrast, the Asia-Africa region shows a promising uptrend from 2012 onwards. This positive trend is driven by research activities in China, South Korea, Japan, and Taiwan. These findings suggest a dynamic and evolving landscape in the field of microfluidic chip research. The shift in geographical focus and the emergence of new players highlight the global interest in this field and the potential for future breakthroughs. It underscores the importance of international collaboration and the need for continued investment in research infrastructure. The increasing trend in the Asia-Africa region also points to the growing influence of these countries in shaping the future direction of microfluidic chip research.

The study reveals that glass and plastics are commonly used as substrates for microfluidic chips due to their good optical clearance, ease of fabrication, and economical production costs. A comparison of the usage of these materials in microfluidic publications from 2012 to 2022 shows a shift in preference. Initially, glass was the preferred substrate, with over 200 publications using it since the early 2000s. However, in recent years, researchers have been favoring more cost-effective substrates like plastic and paper over glass. Despite a slight increase in the use of thermoplastics in the last decade, they remain an attractive material for microfluidic chips in the foreseeable future.

The study of plastic microfluidic chips is a global effort, with 57 countries contributing to the 1608 documents on the subject. The United States leads in publication volume, with China in second place but with a significant gap. The most cited articles are primarily reviews on microfluidic chip materials, originating from the United Kingdom, Germany, the United States, and Hong Kong. Co-authorship mapping reveals four main clusters of collaboration, with the United States, China, and South Korea playing central roles. The most cited articles within these collaborations often focus on the fabrication and application of microfluidic devices. This global collaboration and the high citation rate of review articles indicate the ongoing interest and rapid development in the field of microfluidic plastics.

Based on the results of this bibliometric analysis, we explore possible outlooks to determine future direction. The fabrication method is one of the key areas of interest. Techniques such as hot embossing and injection molding are currently leading, with hot embossing showing the highest link strength among microfabrication techniques. However, the emergence of 3D printing, despite its current lower link strength, indicates a promising direction for future research due to the rapid development of printing technology. The choice of fabrication material is another crucial aspect. PMMA, with its high link strength, is the most preferred material due to its recyclability, ease of fabrication, high optical transmissivity, high-temperature limitation, and biocompatibility. The high optical transmissivity of plastics is particularly relevant, as evidenced by the most cited plastic microfluidic device investigating the auto-fluorescence of PMMA, COC, PS, PDMS. The outermost layer of the bibliometric mapping consists of microfluidic biological-related applications such as immunoassay, PCR, biosensors, cell culture, and bacteria. This suggests that there is a significant interest in applying these devices in biological contexts, particularly given the biocompatibility of polymers such as PDMS and PMMA.

3.5.1. Discussion for the future of plastic microfluidics

The future of plastic-based microfluidics is promising, with several areas of potential growth and innovation. The field of microfluidics has seen significant advancements, particularly in the development of lab-on-a-chip devices, which have revolutionized various biomedical disciplines [87]. The use of plastics in microfluidic devices has been facilitated by the development of suitable microfabrication processes and soft lithography techniques. Plastics offer several advantages such as cost-effectiveness, ease of fabrication, and compatibility with biological samples, making them a practical choice for microfluidic applications [88]. These developments could increase the accessibility of microfluidics to users with both scientific and non-technical backgrounds, thereby broadening the impact of this technology [89]. The future of microfluidic devices lies in exploring new fabrication techniques, developing new materials, expanding their applications in biological fields, and also production scale-up [90]. As an example, the green LOC device, which is strategized by minimizing samples, adopting eco-friendly solvents, and biodegradable plastics composite utilization, is progressing rapidly and will contribute to the future development of plastic microfluidics [91]. Meanwhile, point-of-care devices from sustainable and recycled materials already exist, and several academic and industry groups are developing sustainable POCT applications despite limited visibility for these initiatives. However, we need models demonstrating the technical feasibility and commercial viability of developing single-use diagnostics from local, sustainable materials, with collaborative support from academia, the point-of-care diagnostic industry, and end-users [92].

Moreover, with the introduction of plastic microfluidics, there is a significant opportunity to benefit from the market, which is currently experiencing robust growth, demonstrated by a compound annual growth rate (CAGR) of 15.60 % [93].

4. Conclusions

Following the previous data and analysis, it was revealed that only 20 countries were responsible for nearly 87 % of the total publications, with the US leading in terms of both publication and citation per article. The study also revealed that Asia is leading in microfluidic chip research with nearly twice as many publications as Europe or America, indicating a positive outlook for the future of plastic microfluidic chip research in the Asian region. Based on the result of journal rank analysis, it was found that the journal "Lab on a Chip" is the most active in publishing research on microfluidic chips, with 22.84 % of its publications focused on this area. This information is valuable for researchers looking to publish their work or stay updated on the latest developments. The study also compared the two most engaged microfluidic materials, such as glass and plastic. Plastic is shown to be more attractive for microfluidic chip usage based on the rising trend in the usage of plastic materials. The study highlighted the importance of materials like PDMS, PMMA, PS, and COC in microfluidic research due to their biocompatibility, durability, optical transparency, and cost-effectiveness. By analyzing global trends and keyword networks, the study offers valuable insights for future research topics and directions in plastic microfluidics. This can guide researchers in selecting impactful and relevant areas for their studies.

This study primarily relies on publications from specific databases of Scopus, which may not cover all relevant research in this field. This bibliometric study used citation counts as a measure of impact, which can be influenced by various factors unrelated to the quality of the research. Different disciplines also have varying citation behaviors. Furthermore, this analysis might not account for the most recent developments if the data collection period ends before the latest research is published. Thus, it is suggested to broaden the data sources, combine bibliometrics with qualitative analysis, and use updated data for future bibliometrics of thermoplastic microfluidic studies.

CRediT authorship contribution statement

Rhesa Muhammad Faisal: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Olusola Olaitan Ayeleru:** Writing – review & editing, Supervision, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Helen Uchenna Modekwe:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Ishmael Matala Ramatsa:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Data availability statement

Data included in article/supp. material/referenced in article.

Additional information

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Declaration of competing interest

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

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