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A scientometrics investigation of magnetic nanofluids

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ABSTRACT

The control of thermophysical, fluid flow, and structure of nanofluids using a magnetic field has attracted the focus of many recent researchers in the field. Despite the broad range and application of the magnetic nanofluids, there is no scientometric or thematic analysis revealing the number and distribution of the publications and citations in the field and dynamic maps of the connection of the authors, institutions, and countries. The current research aims to comprehensively analyze the publications and dynamic world network connections of authors, institutes, and countries. Recent five-year publications (2018–2022) were retrieved from the Clarivate database (2224 documents) and were analyzed using an in-house code. The VOSViwer software was also used for the plot of the maps. The results showed Chamkha, Ali J was the most productive author (104 publications) and also the most cited author in the field (2029 citations) with the highest H-Index (33). Babol Noshirvani University has the highest rank among top universities concerning two different parameters: total citations and citations per paper. King Khalid University and Islamic Azad University have the highest rank in total publications and h-index. The highest number of publications also belonged to India, Pakistan, and Saudi Arabia. Moreover, these countries were also influential contributors to MNF, and other countries were linked to these three countries.

1. Introduction

Nanofluids are synthesized as a stable suspension of one or more nanoparticles uniformly dispersed in a liquid. The nanofluids are well-known for their improved heat transfer properties [1,2]. A nanofluid with electrical conductivity or magnetic particles could react to an external magnetic field [1,3,4]. The combination of a magnetic field and nanofluids (MNF) could be divided into two major categories: ferrofluids and magnetohydrodynamic (MHD) flows.

Ferrofluids are suspensions of fine magnetic particles stably dispersed in a host liquid. The magnetic particles are typically made of iron, iron oxides, and maghemite. The host fluid could also be engine oil, transformer oil, ethylene glycol, or water. There is a technical difference between ferrofluids and the typical magneto-rheological fluids (MRF). The ferrofluids are synthesized by fine particles dispersed in a host fluid, and they remain in a liquid form even under a strong imposed magnetic field (MF) (~10 kG) [5].

However, MRF materials show strong variable viscosity effects under a magnetic field and have applications in clutches and brakes. MRF could show semi-solid behavior under a strong magnetic field [6]. Taking advantage of the change of thermophysical properties of ferrofluids using an exterior MF was considered significant for many applications since the initial synthesis of these liquids in the 1960s [7]. Thus, many research and emerging applications have focused on these fluids, such as actuators, seals, sensors, optics, and lubrication [4].

The movement of an electrical conductive nanofluid in an external magnetic field imposes a force on the fluid, which could be used to control the nanofluid motion and its heat transfer characteristics [8]. In recent years, the combination of nanofluids and MHD has found ever-increasing interest [9,10].

Recent researchers have reviewed various aspects of nanofluids and magnetic fields due to the significance of these fluids in recent

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Table 1
Total publications and citations per year.

Year	TP	TC	>200	>100	>50	>25	>10	>5	>1
2018	347	8763	1	11	46	114	216	263	317
2019	470	10,040	1	7	45	129	259	324	421
2020	498	6753	0	1	22	72	205	305	412
2021	629	3723	0	1	9	28	99	197	371
2022	280	671	0	0	1	7	15	26	74
Total	2224	29,950	2	20	123	350	794	1115	1595
%	100%	–	0.09%	0.90%	5.53%	15.74%	35.70%	50.13%	71.72%

TC = total citations > 200, >100, >50, >25, >10, >5, >1 = number of publications having>200, 100, 50, 25, 10, 5 and 1 citations.

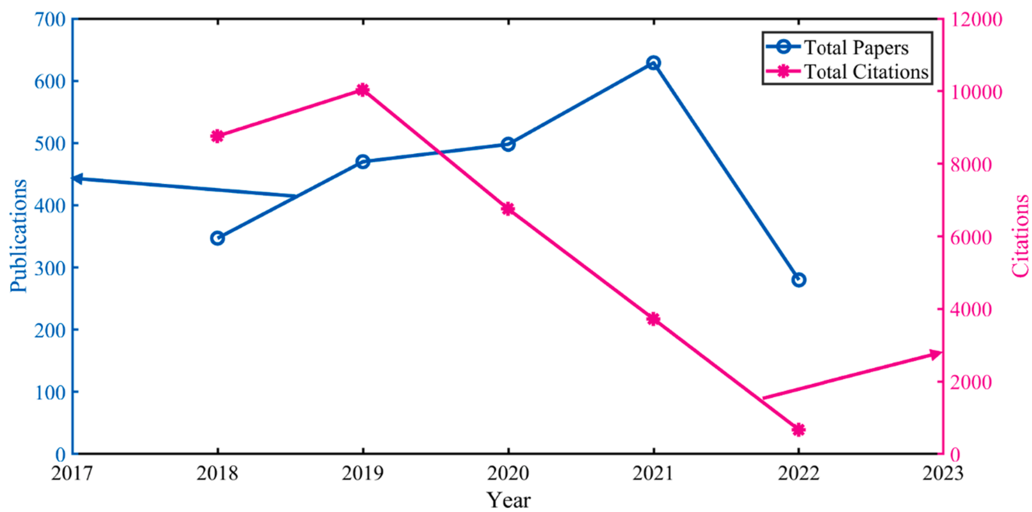


Fig. 1. Time history of total publications (TP) and total citations (TC).

technological advancements. For example, Wang et al. [11] surveyed the heat transfer of nanofluids under an external electrical or magnetic field. Their study indicates that an external field could notably influence the heat transfer benefit of nanofluids. Nkurikiyimfura et al. [12] reviewed the suitability of magnetic nanofluids in photovoltaic/thermal systems. These nanofluids were found promising, but their practice requires further research. The preparation and convection [13], thermophysical properties [14], and solar application [12,15] of magnetic nanofluids have been explored in recent years.

Some studies fundamentally investigated the MHD nature of magnetic fluids in boundary layers over stretching sheets [16–18] and plates [19]. Another important aspect of magnetic nanofluids is their convective heat transfer in enclosures where the flow and heat transfer physics are coupled [20–22]. In some cases, there are porous media [23,24] and wavy surfaces [25], and in some cases, there are active mechanical elements such as lid-driven [26] or a rotating cylinder [27]. Moreover, some researchers considered a two-phase model for the analysis of the migration of nanoparticles in MHD flows [28,29]. The deposition of nanoparticles is another aspect addressed in [30].

The literature review shows that there is no scientometric analysis and thematic evolution of magnetic nanofluids. For the first time, the present study aims to address the following questions in magnetic nanofluids: (1) what are the most influential scholars, countries, and affiliations contributing to the advancement of magnetic nanofluids? (2) What are the most cited articles, institutions, and countries? (3) How are the field's word dynamic and thematic map? and (4) how authors, articles, institutions, and countries are connected?

2. Methods

In the present study, the bibliographic data of publications contributed by MNF for the last five years has been retrieved from the Web of Science (WOS) database.

The following search formula was used to extract data related to the nanofluids, magnetic and magnetic effects, and nanotechnology: (nanofluid* AND (magnet* OR MHD OR magnetism*)) OR (ferrofluid* NEAR (nanoparticles OR nano*additives)). The search strings were used in the title of papers published in recent five years. In the first part of the search string, the word nanofluid and its substitutes (nanofluid*) were linked to magnetic. In the second part of the string, ferrofluids were approximated to nanoparticles or nano additives. The NEAR operator considers word proximity within 15 words. The star symbol also considers any arbitrary character in the word.

A total of 2224 documents were found. The VOSviewer software was employed to evaluate the data. The citation details, h-index, and tables were computed by an in-house code developed by the authors. VOSviewer mapping and clustering were used for Bibliographic mapping and clusters.

In the following sections, the outcomes are presented in the sections. Firstly, the bibliography is analyzed in the form of charts and tables. Secondly, network visualization is performed: co-citation, coupling of authors, universities, countries, and co-authorships were investigated in the second part.

3. Bibliometric analysis

The present section presents publications and citations per year, authors with the highest productivity and influence, universities with the highest productivity and influence, and countries with the highest productivity and influence.

3.1. Yearly publications and citations

The first point is to assess the history of publication and citation of

Table 2
Forty leading authors in MNF.

R	Author name	Affiliation	Country	TP	TC	HI	TC/TP
1	Chamkha, Ali J.	Kuwait Coll Sci & Technol; Prince Mohammad Bin Fahd Univ; Duy Tan Univ	Kuwait Saudi Arabia Vietnam	104	2909	33	28
2	Khan, Ilyas	Majmaah Univ; Ton Duc Thang Univ	Saudi Arabia Vietnam	61	963	19	16
3	Shah, Zahir	Univ Lakki Marwat; King Mongkuts Univ Technol; Thonburi KmuttAbdul Wali Khan Univ	Pakistan Thailand	57	1370	22	24
4	Pop, Ioan	Babe Bolyai Univ	Romania	56	1080	22	19
5	Khan, M.	Quaid I Azam Univ; Chinese Acad Sci	Pakistan China	50	952	18	19
6	Oztop, Hakan F.	Firat Univ; China Med Univ	Turkey Taiwan	50	1033	20	21
7	Sheikholeslami, M.	Babol Noshirvani Univ Technol	Iran	49	2895	27	59
8	Muhammad, Taseer	King Khalid Univ	Saudi Arabia	47	299	7	6
9	Nisar, K. S.	Prince Sattam Bin Abdulaziz Univ	Saudi Arabia	40	283	11	7
10	Kumam, Poom	King Mongkuts Univ Technol; Thonburi KmuttChina Med Univ	Thailand Taiwan	39	605	15	16
11	Alsaedi, Ahmed	King Abdulaziz Univ	Saudi Arabia	38	880	18	23
12	Rashad, A. M.	Aswan Univ	Egypt	38	783	15	21
13	Selimefendigil, F.	Celal Bayar Univ	Turkey	37	908	18	25
14	Islam, Saeed	Abdul Wali Khan Univ; Ton Duc Thang Univ	Pakistan Vietnam	34	807	17	24
15	Ganji, D. D.	Babol Noushirvani Univ Technol	Iran	33	1635	25	50
16	Shehzad, Sabir Ali	Comsats Univ Islamabad	Pakistan	31	717	13	23
17	Waqas, Hassan	Govt Coll Univ Faisalabad	Pakistan	31	422	11	14
18	Chu, Yu Ming	Huzhou Univ	China	30	249	10	8
19	Khan, Waqar A.	Prince Mohammad Bin Fahd Univ	Saudi Arabia	29	603	14	21
20	Bhatti, M. M.	Shandong Univ Sci & Technol	China	26	872	16	34
21	Khan, M. Ijaz	Quaid I Azam Univ; King Abdulaziz Univ	Pakistan Saudi Arabia	26	482	10	19
22	Malik, M. Yousaf	King Khalid Univ; Quaid I Azam Univ	Saudi Arabia Pakistan	26	348	11	13
23	Nadeem, Sohail	Quaid I Azam Univ; Ton Duc Thang Univ	Pakistan Vietnam	26	585	15	23
24	Ramzan, M.	Bahria Univ	Pakistan	26	373	12	14
25	Hayat, Tasawar	Quaid I Azam Univ; King Abdulaziz Univ	Pakistan Saudi Arabia	25	531	14	21
26	Mansour, M. A.	Assiut Univ	Egypt	25	509	11	20
27	Afrand, Masoud	Islam Azad Univ; Ton Duc Thang Univ	Iran Vietnam	22	613	13	28
28	Dogonchi, A. S.	Islamic Azad Univ	Iran	22	949	18	43
29	Tlili, Iskander	Duy Tan Univ; Majmaah Univ	Vietnam Saudi Arabia	22	765	17	35
30	Beg, Osman Anwar	Univ Salford	England	21	257	9	12
31	Jamshed, Wasim	Capital Univ Sci & Technol Cust	Pakistan	21	202	8	10
32	Khan, Sami Ullah	Riphah Int Univ	Pakistan	21	300	9	14
33	Shafie, Sharidan	Univ Teknol Malaysia	Malaysia	21	181	8	9
34	Ahmed, Sameh E.	King Khalid Univ	Saudi Arabia	20	194	7	10
35	Prasannakumara, B. C.	Davangere Univ	India	20	262	9	13
36	Sheremet, M. A.	Tomsk State Univ	Russia	20	755	12	38
37	Gul, Taza	City Univ Sci & Informat Technol	Pakistan	19	280	8	15
38	Hussain, S.	Capital Univ Sci & Technol Cust	Pakistan	19	216	10	11
39	Kadry, Seifedine	Noroff Univ Coll; Beirut Arab Univ	Norway Lebanon	19	246	8	13
40	Khan, Masood	Quaid I Azam Univ	Pakistan	19	285	11	15

HI = h-index (MNF).

MNF in the last five years (2018–2022). The total number of publications (TP) and citations (TC) for every publication year are illustrated in Table 1 and Fig. 1. In addition, the table specifies the number of articles that exceeded a given citation number: 200, 100, 50, 25, 10, 5, and 1 citation are considered.

Table 1 indicates that around 72% (1595/2224) of publications have been cited at least once, and around 50% (1115/2224) of publications have been cited five times at least. Generally, both the total numbers of publications and citations rise with time.

The yearly number of publications cited over ten times each peaked in 2019 and remained high in 2020 but decreased substantially in 2021 and 2022. This decrease can be explained by the time difference between publishing a given article and its citation by future published articles. For instance, the articles published in 2021 and 2022 have not yet received citations due to their recent publication dates.

3.2. Authors with the highest productivity and influence

In the present section, the top authors publishing articles in MNF are identified. Table 2 shows the highest 40 authors ranked considering the number of their published papers. Based on the number of MNF papers, the top author is Chamkha, Ali J., with 104 published articles. With this number, the number of publications of Chamkha is almost twice the one corresponding to the author in the second rank. After Chamkha, eight authors who authored 40 or more articles in MNF are identified: Khan I. (61 articles), Shah (57), Pop (56), Khan M. (50), Oztop (50), Sheikholeslami (49), Muhammad (47) and Nisar (40). All the top 40 authors have at least 19 publications each in MNF.

Among the aforementioned authors, Chamkha, Ali J is also the one who received the most citations. The 104 papers authored by Chamkha earned 2909 citations. Moreover, Chamkha authored a highly-cited MNF paper entitled “Thermal radiation and surface roughness effects on the thermo-magneto-hydrodynamic stability of alumina-copper oxide hybrid nanofluids utilizing the generalized Buongiorno’s

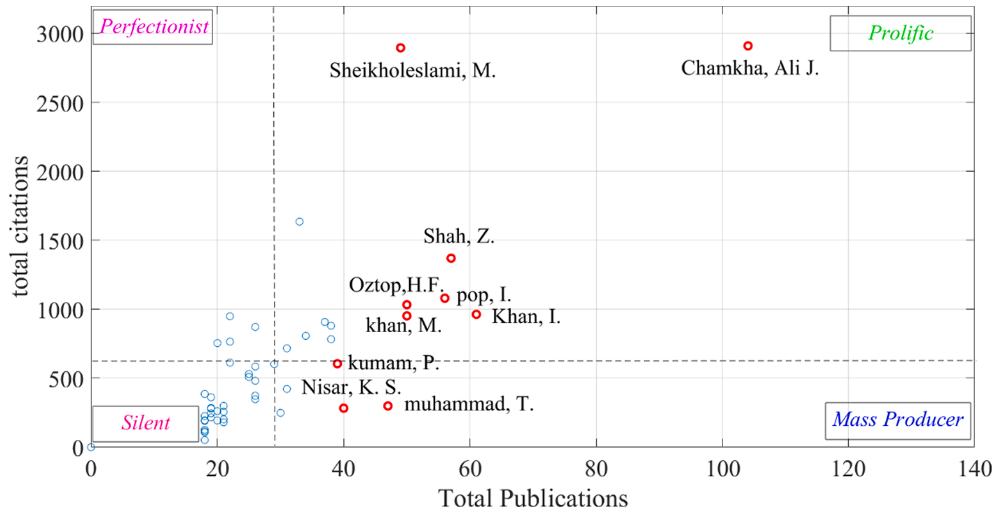


Fig. 2. Authors ranked with respect to total numbers of published papers and citations.

nanofluid model [31]" in which the authors investigate the impact of thermal radiation and surface roughness on the dynamics of water containing alumina and copper oxide nanoparticles. They considered the change of the thermophysical properties of the resulting mixture with the nanoparticle concentration, the Brownian motion, and thermophoresis phenomena. In addition, Chamkha has three other articles that were cited>100 times each "Hall and ion slip effects on MHD rotating boundary layer flow of nanofluid past an infinite vertical plate embedded in a porous medium [32]", "Entropy generation and MHD natural convection of a nanofluid in an inclined square porous cavity: effects of a heat sink and source size and location [33]" and "Magnetohydrodynamic flow and heat transfer of a hybrid nanofluid in a rotating system among two surfaces in the presence of thermal radiation and Joule heating [34].".

The author that received the second-highest citation number is Khan, Ilyas, with 2895 citations for 49 publications. He is followed by Ganji, D. D., who earned 1635 citations for 33 publications. Of the 40 authors with the highest number of publications in MNF, 25 have been cited>400 times each. As shown in Table 2, 17 authors have h-indices higher or equal to 15 (the h-indices in the table are determined based only on the published papers in MNF). Chamkha, Ali J. and Sheikholeslami, M, have the highest h-indices (33 and 27, respectively). This indicates that Chamkha has 33 publications cited at least 33 times each, and Sheikholeslami has 27 publications cited at least 27 times each.

Fig. 2 shows the different authors with respect to their total number of published papers and the earned citations. Following [35], scholars can be classified into four categories according to 2 criteria: productivity and citation. An author with many publications and many citations is considered Prolific. An author with a large number of publications but a small number of citations is considered a Mass producer. An author with a small number of publications but a large number of citations is considered a Perfectionist. Finally, an author with a small number of publications and a small number of citations is considered a Silent author. Based on this classification, and relatively to the remaining authors, Chamkha is prolific, while Sheikholeslami is a perfectionist. Most of the remaining authors are grouped near the lowest part of the graph.

3.3. Universities with the highest productivity and influence

Table 3 shows the top 40 institutional affiliations of authors ranked by the number of published papers in MNF. Considering the TP index, King Khalid University, King Abdulaziz University, Islamic Azad University, and Quaid I Azam University are at the top of the table. With a brief look at Table 3, it can be seen that from the index of TC, the University of Babol Noshirvani University of Technology (3518) has the highest number of citations, followed by Islamic Azad University (3242), Ton Duc Thang University (2336) and Quaid I Azam University. (2318), which are in the next ranks of the table. In addition, according to the HI index, four universities, including Islamic Azad University (36), Babol Noshirvani University of Technology (35), Prince Mohammad Bin Fahd University (32), and Ton Duc Thang University (30), are at the top of the table, respectively. Finally, Babol Noshirvani University of Technology (50), the American University of Ras Al Khaimah (41), Prince Mohammad Bin Fahd University (35), and the Islamic Azad University (26) have the highest number average in terms of TC/TP index. Considering these indicators, no university is absolutely superior to another university. Islamic Azad University is among the top four universities based on all four indicators.

Overall, universities in Pakistan (10 university) dominate the ranking, followed by Saudi Arabia (7 university) and Egypt (5 university). Quaid I Azam University is also in the top four universities in terms of the TP index and TC index. Fig. 3 illustrates universities mapped with respect to the number of published papers and earned citations. A relationship between the number of papers and the number of citations for each institution can be noticed. Fig. 3 shows that many of the universities are in the Silent area. Four universities: Islamic Azad University, Ton Duc Thang University, Quaid I Azam University, and King Abdulaziz University, are moving toward prolific. China Med Univ and Prince Sattam Bin Abdulaziz Univ are moving towards mass production. Almost no university is located in the perfectionist area, indicating that TC is heavily dependent on TP. In fact, no university can achieve high TC with low TP.

3.4. Countries with the highest productivity and influence

Table 4 summarizes the statistics of the top 40 countries in the number of total publications compared to the population. This population is included to address the productivity per million population and research and the country's investments in research and development as a percentage of the country's GDP. Regarding TP, India leads the ranking, followed by Pakistan, Saudi Arabia, Iran, and China. in terms of total citations and h-index, these countries are in the top five countries on the table by changing their position. According to the table, it can be seen that India, despite having the highest TP but among the top five countries in the table, has the lowest TC. Pakistan also has the highest number of publications compared to the research and development investment of the country. The maximum number of both publications (TP/Pop) and the total citation per (TC/Pop) million residents was achieved by the Kingdom of Saudi Arabia, followed by the State of

Table 3
Top institutional affiliations of authors publishing in MNF*.

R	Name	Country	TP	TC	HI	TC/TP
1	King Khalid Univ	Saudi Arabia	163	1380	19	8
2	King Abdulaziz Univ	Saudi Arabia	151	2187	28	14
3	Islamic Azad Univ	Iran	123	3242	36	26
4	Quaid I Azam Univ	Pakistan	120	2318	28	19
5	Ton Duc Thang Univ	Vietnam	107	2336	30	22
6	Prince Sattam Bin Abdulaziz Univ	Saudi Arabia	99	715	15	7
7	Comsats Univ Islamabad	Pakistan	84	1048	18	12
8	Prince Mohammad Bin Fahd Univ	Saudi Arabia	76	2694	32	35
9	China Med Univ	Tiwan	72	797	17	11
10	Babol Noshirvani Univ Technol	Iran	70	3518	35	50
11	Abdul Wali Khan Univ	Pakistan	53	943	17	18
12	Babes Bolyai Univ	Romania	53	1036	21	20
13	Firat Univ	Turkey	52	908	18	17
14	Aswan Univ	Egypt	44	825	15	19
15	Huzhou Univ	China	44	339	11	8
16	South Valley Univ	Egypt	43	399	13	9
17	Natl Univ Sci & Technol	Pakistan	40	424	13	11
18	Univ Kebangsaan Malaysia	Malaysia	39	689	16	18
19	Majmaah Univ	Saudi Arabia	37	607	13	16
20	Celal Bayar Univ	Turkey	36	866	18	24
21	Duy Tan Univ	Vietnam	35	507	14	14
22	Amer Univ Ras Al Khaimah	U.A. Emirates	34	1406	25	41
23	Bahria Univ	Pakistan	34	613	16	18
24	Hazara Univ	Pakistan	34	499	13	15
25	Jadavpur Univ	India	33	328	11	10
26	Ain Shams Univ	Egypt	32	233	8	7
27	Riphah Int Univ	Pakistan	32	423	11	13
28	Taif Univ	Saudi Arabia	32	105	5	3
29	Assiut Univ	Egypt	30	559	12	19
30	Govt Coll Univ Faisalabad	Pakistan	30	250	9	8
31	King Mongkuts U. T. Thonburi	Thailand	30	361	11	12
32	Capital Univ Sci & Technol	Pakistan	29	376	13	13
33	Menoufia Univ	Egypt	29	242	10	8
34	Int Islamic Univ	Pakistan	28	573	12	20
35	Osmania Univ	India	28	162	5	6
36	Kuwait Coll Sci & Technol	Kuwait	27	111	8	4
37	Natl Inst Technol	India	27	279	12	10
38	Sejong Univ	South Korea	27	394	12	15
39	King Fahd Univ Petr & Minerals	Saudi Arabia	26	743	12	29
40	King Saud Univ	Saudi Arabia	25	210	9	8

Kuwait, and finally, the United Arab Emirates. Fig. 4 shows most of the top countries in the list are placed in a silent zone, and there is no country in the perfectionist zone. Egypt is marginally in the mass producer zone. Pakistan is well prolific. Moreover, Saudi Arabia, Iran, China, and India are also placed in the prolific zone.

3.5. Distribution of countries, institutions, and authors

Table 5 and Fig. 5 present statistics on the number of authors, their corresponding institutions, and countries during the last five years. It is clear from Fig. 5 that during the first year of MNF publications, the numbers of authors and institutions are sharply rising except for the current year, 2022. Moreover, the changes in the number of countries are minimal.

Table 5 shows the distribution trend of authors, universities, and countries over a period of 5 years. A brief look at Table 5 can show that the trend in the number of publications has had an upward trend from 2018 to 2021. The number of publications, countries, and institutions in 2022 has been lower than in previous years, perhaps due to its location in the middle of 2022. Therefore, it is not yet clear. It can also be seen from the table that from 2020 to 2021, there is a significant jump in terms of increasing the number of institutions, the number of institutions as well as the number of publications from 2018 to 2021 has an upward trend.

The following section discusses the network visualization maps in the following section.

4. Network visualization

Here, network visualization is presented: author co-citation; co-authorship; and author, institution, and country bibliographic coupling.

4.1. Co-citation

Co-citation happens when two publications are cited by the same paper (Cancino et al., 2017). Co-citation is analyzed as it is assumed that the two corresponding publications should be highly related (White and Griffith, 1981). Therefore, publications with co-citation should be mapped in a cluster solution. Fig. 7 illustrates a co-citation analysis in MNF in the form of a network visualization map. The 50 authors with the most representation in the field are included in this network. Every author is represented by a circle (node), and co-citations (relation to other authors) are symbolized by the lines (links) connecting the nodes. The map is analyzed as follows. The shorter the distance between the authors, the stronger the relationship between authors (Van Eck and Waltman, 2019). Each node has a weight representing the strength of the links connected to it. A node with a higher weight is represented by a larger circle and a larger name of the author.

The map in Fig. 7 depicts Four numbered clusters. Authors Hayat, Choi, and Khan anchor the first one (Red with 26 authors) and Buongiorno. Hayat has the top total link strength in the second cluster with a score of 30433. The second cluster (green with 17 authors) is anchored by authors Sheikholeslami, Selimefendigil, Chamkha and Dogonchi. Sheikholeslami had the top total link strength in the second cluster with a score of 37,893 and publications of 49, followed by Selimefendigil, Chamkha and Dogonchi. Although Chamkha has the highest number of TPs and TCs compared to Sheikholeslami, Sheikholeslami has established the total link strength. Ellahi anchors the third one (Blue with five authors). Ellahi has Total Link Strength of 6252 and has published 17 articles. Hatami anchors the fourth cluster (yellow with two authors).

4.2. Co-authorships

Collaboration in research is widely undergone through co-authorship. By participating in one or more publications, authors are linked together through a social network of co-authorship. This network is analyzed in the present paper by studying a network of 2224 publications in MNF in the period 2018–2022.

Fig. 8 shows the co-authorship network of publications in MNF. A node represents each author, and a link connecting two nodes indicates a co-authorship between the corresponding authors. A minimal publication threshold of 10 documents and 300 links is considered. These authors are divided into 7 clusters. According to the number of connections, Shah and Chamkha have the highest number, with 88 and 82 total link strengths, respectively. The top five authors after Chamkha who have the total link strength are Alsaedi, Kumam, Sheikholeslami, Islam, and Oztop. Despite the fact that the number of total papers and total citations of Chamkha is almost twice that of Shah, Shah has the total link strength.

4.3. Bibliographic coupling

Bibliographic coupling happens when two publications cite the same publication. This coupling is considered stronger when two documents

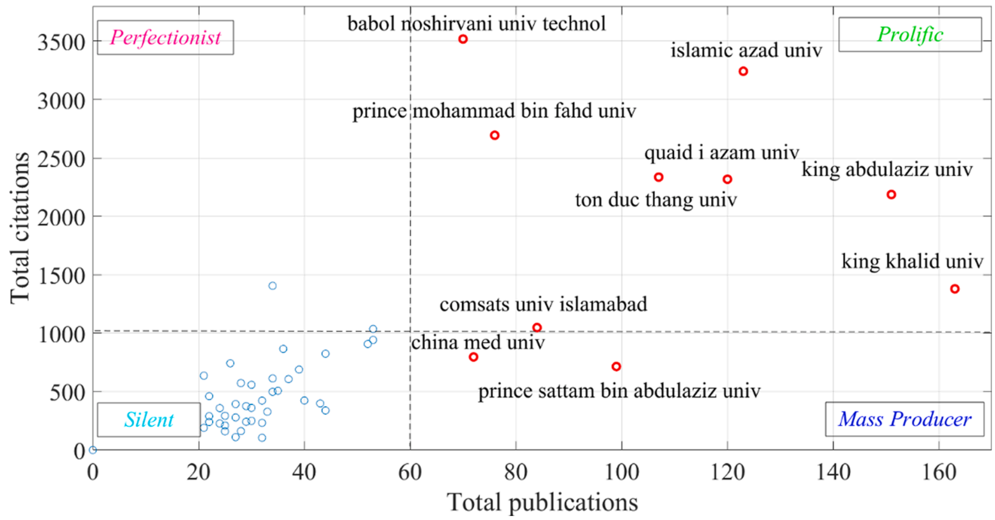


Fig. 3. Universities mapped by number of published research papers and their number of citations.

Table 4
Countries with the highest productivity and influence in MNF.

R	Country	TP	TC	HI	TC/ TP	Pop	TP/ Pop	TC/ Pop	R&D	TP/ R&D	TC/ R&D
1	India	651	5570	32	8.6	1380	0.47	4	0.65	997.2	8.5
2	Pakistan	645	9494	46	14.7	220.9	2.92	43	0.24	2729.9	40.2
3	Saudi Arabia	566	8882	48	15.7	34.8	16.26	255.1	–	–	–
4	Iran	335	8739	50	26.1	84	3.99	104	0.83	403.5	10.5
5	China	310	5001	40	16.1	1410.9	0.22	3.5	2.14	144.8	2.3
6	Egypt	213	2287	27	10.7	102.3	2.08	22.3	0.72	294.2	3.2
7	Malaysia	152	2083	29	13.7	32.4	4.7	64.4	1.04	146	2.0
8	Vietnam	138	2799	31	20.3	97.3	1.42	28.8	0.53	262	5.3
9	Turkey	116	1636	23	14.1	84.3	1.38	19.4	0.96	120.9	1.7
10	Taiwan	92	1017	19	11.1	–	–	–	–	–	–
11	Romania	81	1316	24	16.2	19.3	4.2	68.2	0.5	161.8	2.6
12	Thailand	69	1173	21	17	69.8	0.99	16.8	1	68.9	1.2
13	U Arab Emirates	64	2241	32	35	9.9	6.47	226.6	1.28	50.1	1.8
14	USA	63	1410	19	22.4	329.5	0.19	4.3	2.83	22.2	0.5
15	South Africa	60	790	17	13.2	59.3	1.01	13.3	0.83	72.1	0.9
16	South Korea	52	535	14	10.3	51.8	1	10.3	4.53	11.5	0.1
17	Bangladesh	47	274	10	5.8	164.7	0.29	1.7	–	–	–
18	Algeria	46	821	14	17.8	43.9	1.05	18.7	0.54	84.7	1.5
19	Kuwait	44	1086	15	24.7	4.3	10.3	254.3	0.06	705.4	17.4
20	Iraq	43	771	16	17.9	40.2	1.07	19.2	0.04	990.3	17.8
21	Tunisia	43	605	13	14.1	11.8	3.64	51.2	0.6	71.5	1.0
22	England	42	968	18	23	67.2	0.62	14.4	1.7	24.7	0.6
23	Australia	41	988	18	24.1	25.7	1.6	38.5	1.87	21.9	0.5
24	Russia	37	796	12	21.5	144.1	0.26	5.5	0.98	37.6	0.8
25	Nigeria	36	511	10	14.2	206.1	0.17	2.5	–	–	–
26	Ethiopia	28	107	5	3.8	115	0.24	0.9	0.27	102.1	390
27	Canada	24	378	9	15.8	38	0.63	9.9	1.54	15.6	245
28	Jordan	23	206	8	9	10.2	2.25	20.2	–	–	–
29	Italy	17	157	8	9.2	59.6	0.29	2.6	1.39	12.2	112.8
30	Morocco	17	519	10	30.5	36.9	0.46	14.1	–	–	–
31	Lebanon	16	232	7	14.5	6.8	2.34	34	–	–	–
32	Oman	16	113	5	7.1	5.1	3.13	22.1	0.22	72.8	514.4
33	Greece	15	138	6	9.2	10.7	1.4	12.9	1.18	12.7	117.2
34	Singapore	12	100	7	8.3	5.7	2.11	17.6	1.92	6.2	52
35	Germany	11	81	4	7.4	83.2	0.13	1	3.13	3.5	25.9
36	Sudan	11	200	6	18.2	43.8	0.25	4.6	–	–	–
37	Ghana	10	322	8	32.2	31.1	0.32	10.4	–	–	–
38	Kazakhstan	10	160	6	16	18.8	0.53	8.5	0.12	85.6	1369.5
39	Scotland	10	172	6	17.2	–	–	–	–	–	–
40	Botswana	9	125	4	13.9	2.4	3.83	53.2	–	–	–

Pop: milion person.

share a higher number of citations of other third publications. As indicated by Martyn (1964), “two papers that share one reference contain one unit of coupling, and the value of a relationship between two papers having one or more references in common is stated as being of strength one, two, etc., depending on the number of shared references.” Therefore, the bibliographic coupling is an effective means to analyze the similarity between publications, authors, universities, or countries. It is based on assuming that two publications citing the same paper should be highly related together and can be mapped into a network of bibliographic coupling.

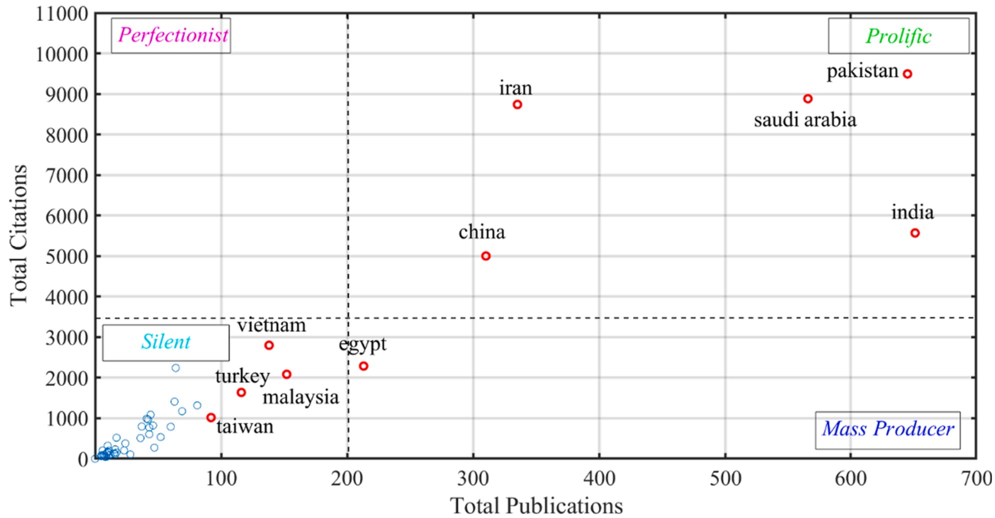


Fig. 4. Countries mapped according to the research papers (TP) and citations (TC).

Table 5
Total publications, Countries, Authors, and institutions over time.

Year	TP	Countries	Authors	Institutions
2018	347	57	789	428
2019	470	53	1049	555
2020	498	61	1136	613
2021	629	64	1487	808
2022	280	45	790	479

Fig. 9 represents the bibliographic coupling between authors and helps measure the strength of the connection between authors. The map shows five defined clusters and the links between the authors. Concerning authorship, ten documents and 200 citations per author are considered to collect the author's link strength. Among the 3474 authors, 74 authors are considered with this threshold. Chamkha is ranked in the top position, as he has received 93,206 total link strength, followed by Pop and Shah, who have 68,010 & 59,271 link strength, respectively.

Fig. 10 shows the bibliographic coupling network between institutions in MNF. A threshold of 10 publications with 200 citations per institution is considered for institutions. 1458 institutions have been linked and collaborated in the research. Among these 1458 institutions, only 74 meet the defined threshold. Table 6 reveals the top ten institutions' documents, citations, and link strength. King Khalid University, Saudi Arabia (165305) has the highest link strength, followed by King Abdulaziz University (163925 link strength) and Islamic Azad University (136205 link strength). Among the top 10 linked institutions, there are four universities from Saudi Arabia.

The bibliographic coupling of countries in MNF is presented in Fig. 11. Countries' bibliographic coupling happens when papers from 2 countries cite papers from a third one. In this regard, 81 countries have had research collaboration in the field. A threshold of 10 documents and 200 citations per country is considered. Only 31 countries meet this threshold. Fig. 11 suggests that Saudi Arabia, Pakistan, and India have the most influence in MNF and that the remaining countries are linked to these countries. Table 7 reveals that the country with the highest link strength is Pakistan (860809 link strength), followed by Saudi Arabia (806616 link strength) and India (771107 link strength).

The top 15 articles with the most citations published in MNF are presented in Table 8. The publication year, authors, the paper title, and a representative figure are listed in the table. Moreover, a summary of the topic and main findings are reported below each article.

5. Concluding remarks

The present research provides an overview of publications and yearly citations in MNF, along with an analysis of the authors, institutions, and countries with the highest productivity and influence in the past five years. Other parameters such as co-citation, co-authorships, and

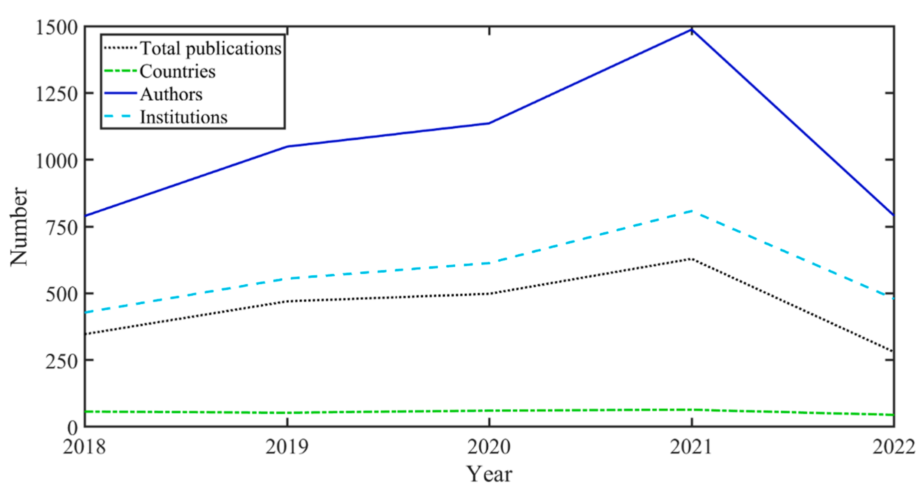


Fig. 5. Variation of author, institution, and country numbers with time TP = Total Publications.

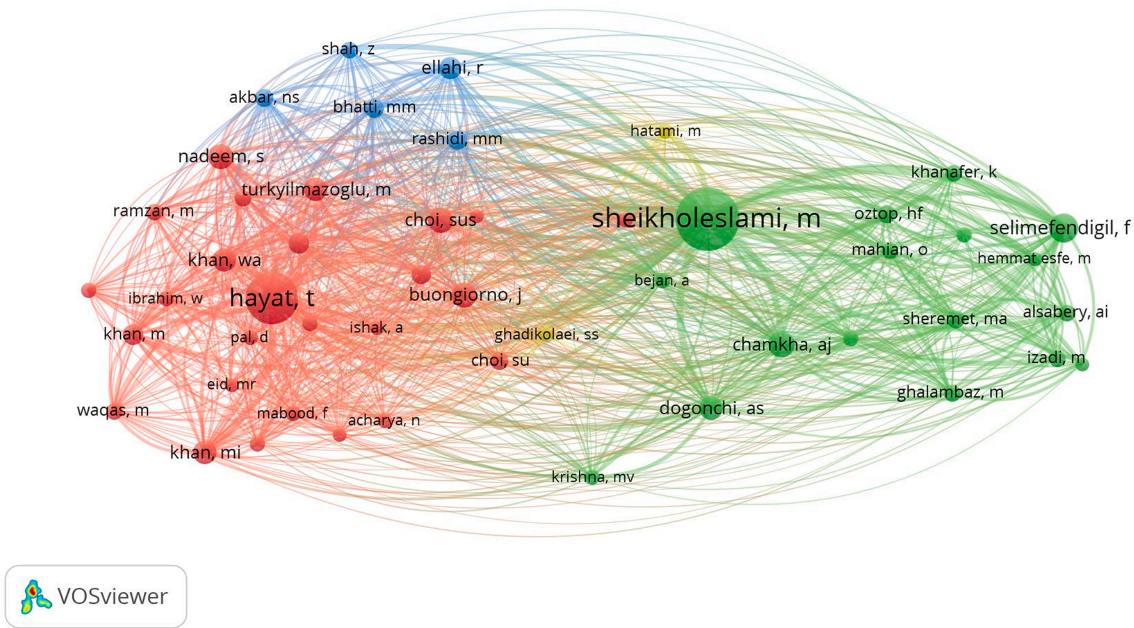


Fig. 7. Co-citation network visualization map of MNF.

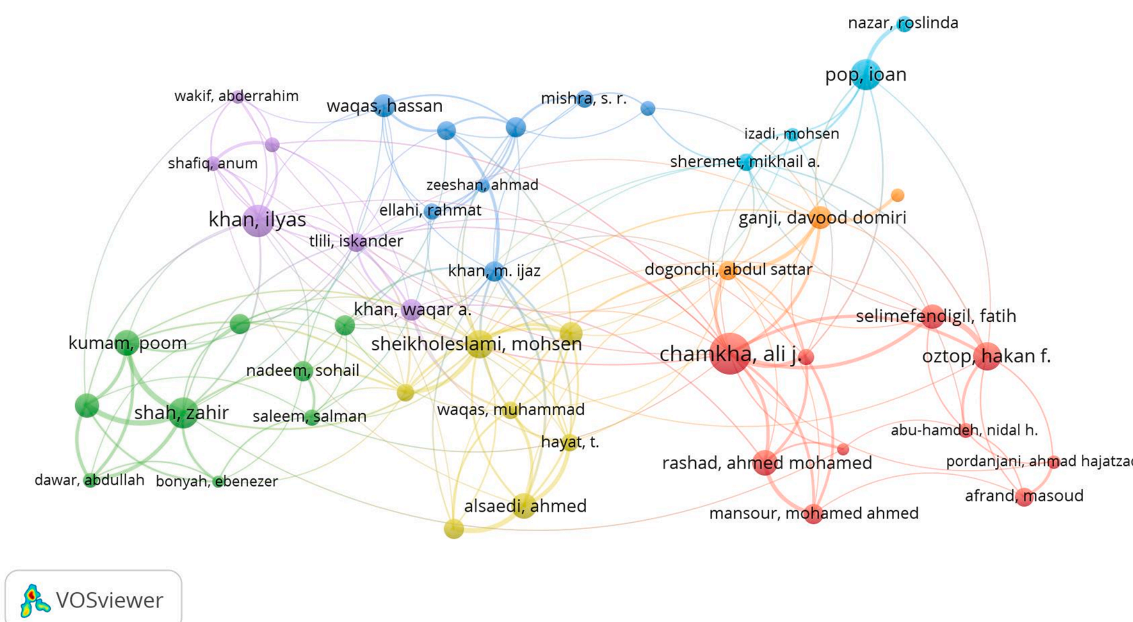


Fig. 8. Co-authorship network visualization in MNF. A minimum threshold of ten publications with 300 links was considered to produce the map.

bibliographic coupling are also analyzed. The objective of this research was to define the authors, universities, and countries that have the most influence in generating knowledge in the MNF field. To fulfill this goal, bibliographic information provided by the WOS Core Collection database was analyzed through the description, tables, and graphs.

For Authors, Chamkha, Ali J was certainly the most productive author, with the highest number of papers in MNF and 1.7 times more publications than the second productive author. Thirty-six authors have contributed to>20 publications each in MNF.

Chamkha was not only the author with the highest number of publications in MNF but also the author with the highest number of citations (2909). Particularly, Chamkha authored a top-cited MNF paper titled “thermal radiation and surface roughness effects on the thermo-magneto-hydrodynamic stability of alumina-copper oxide hybrid nanofluids utilizing the generalized Buongiorno’s nanofluid model [31].

Chamkha, Ali J. and Sheikholeslami, M, have the highest h-indexes (33 and 27, respectively), which means that Chamkha has 33 publications that received at least 33 citations each. Sheikholeslami has 27 publications that received at least 27 citations each.

Concerning institutions, Babol Noshirvani University has the highest rank with regard to two different parameters: total citations and citations per paper. King Khalid University and Islamic Azad University have the highest rank in total publications and h-index. With respect to citations per paper, Babol Noshirvani’s performance was 525 percent higher than the next ranked university (King Khalid University). This shows that the influence of authors affiliated with Babol Noshirvani University in MNF was considerably strong.

As for countries, the ones with the highest number of publications in

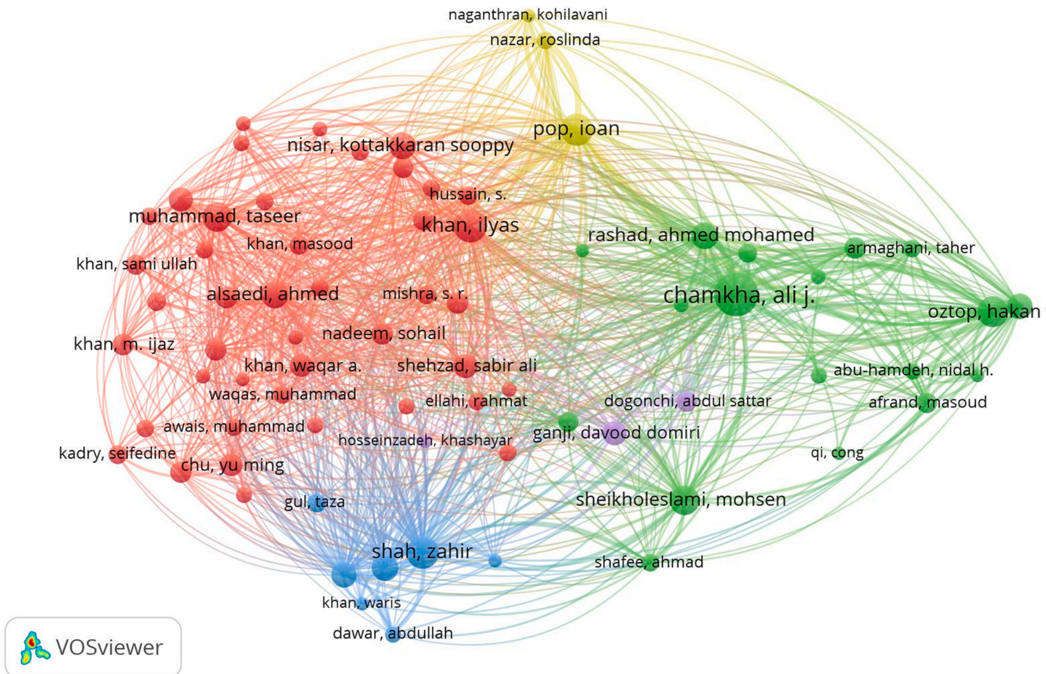


Fig. 9. Author bibliographic coupling in MNF: Minimum threshold of 10 publications with 200 links.

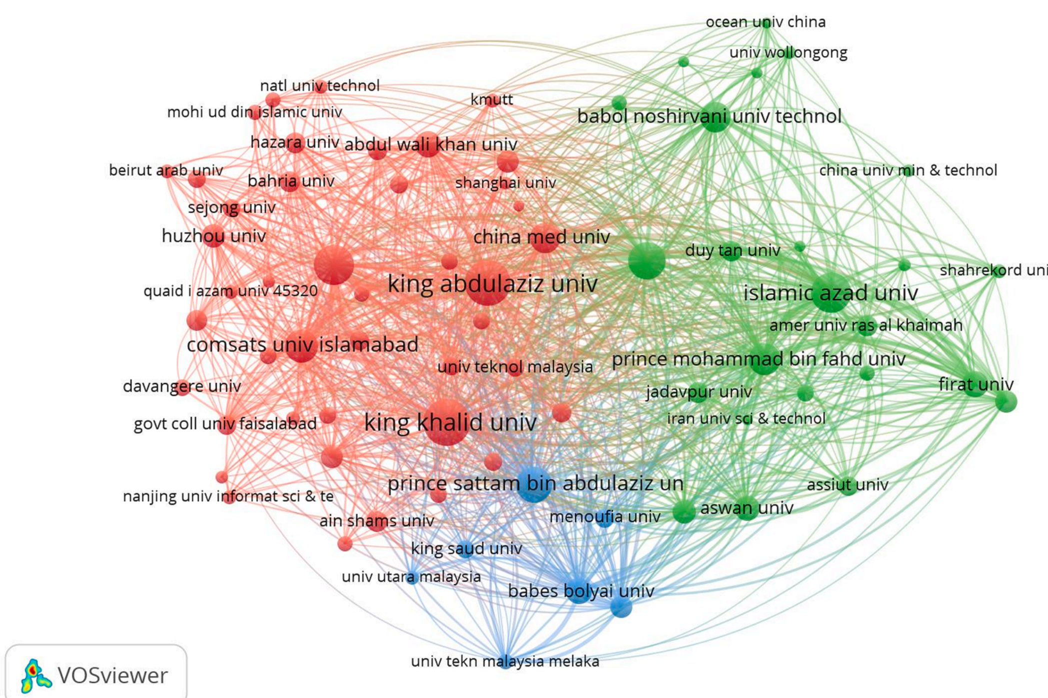


Fig. 10. Institution bibliographic coupling network in MNF. A minimum threshold of 10 publications with 200 links.

MNF were India, Pakistan, Saudi Arabia, Iran, and China. When these numbers were normalized for population size, Middle Eastern countries (Saudi Arabia, Kuwait, United Arab Emirates, and Iran) were the top four countries.

In terms of the Co-citation of authors, there were four clusters, each of which was anchored by specific researchers. Among all the surveyed researchers, the most cited researcher, the most productive researcher, the most highly cited researcher, and the researcher with the highest citations per paper were in the second cluster (green cluster).

This research also examined the co-authorship network of authors and publishing in MNF. The minimum release threshold was 10 documents and 300 links. Authors were divided into 7 clusters. Among all the researchers surveyed, Shah from the second cluster (green) and Chamkha from the first cluster (red) got the highest total link strength. Even though the number of Total publications and Total citations of Chamkha was almost twice that of Shah, Shah gained the highest total link strength.

Bibliographic coupling of authors was considered. A threshold of ten documents and 200 citations per author was taken into account to define the author's link strength. Out of 3474 authors, 74 authors meet this

Table 6
Top-10 institutions with the highest link strength.

R	Institution	Documents	Citations	Total link strength
1	King Khalid Univ, Saudi Arabia	163	1380	165,305
2	King Abdulaziz Univ, Saudi Arabia	151	2187	163,925
3	Islamic Azad Univ, Iran	123	3242	136,205
4	Ton Duc Thang Univ, Vietnam	107	2336	131,660
5	Quaid I Azam Univ, Pakistan	120	2318	129,610
6	Prince Sattam Bin Abdulaziz Univ, Saudi Arabia	99	715	111,832
7	Prince Mohammad Bin Fahd Univ, Saudi Arabia	76	2694	107,205
8	Babes Bolyai Univ, Romania	53	1036	96,685
9	Comsats Univ Islamabad, Pakistan	84	1048	85,556
10	China Med Univ, Taiwan	72	797	82,183

threshold. The bibliographic coupling of authors revealed that the most influential author was Chamkha Ali J. The other influential authors are Khan I., Shah. Z., Pop. I., Oztop H. F., and Sheikholeslami. M.

Bibliographic coupling of countries was also analyzed. After filtering and analyzing, only 31 countries meet the thresholds. Countries were divided into six clusters. The map was anchored by Saudi Arabia, Pakistan, and India. Pakistan and India were in the second (green) cluster, and Saudi Arabia was in the first (red) cluster. Pakistan, India, and Saudi Arabia were influential contributors to MNF, and other countries were linked to these three countries. So, suppose a paper is cited by a publication outside Saudi Arabia, Pakistan, and India. In that case, it is also likely to be cited by someone in Saudi Arabia, Pakistan, and India.

Only 74 institutions met the defined threshold for bibliographic coupling of institutions. King Khalid University in Saudi Arabia received the highest link strength. Among the top ten linked institutions, four universities were from Saudi Arabia and two from Pakistan. Among the top ten universities with the highest link strength, the most share belonged to Saudi Arabia universities with 40%, followed by Pakistanian universities with 20% share.

The subject of the current research was limited to magnetic materials connected with nanofluids or fluids containing nano additives. There are other aspects of magnetic liquids, such as the movement of electrically conductive fluids in a magnetic field, leading to magnetohydrodynamic flows. Thus, future research could consider a broader range of fluids with magnetic field effects or other aspects of fluid motion under the magnetic field effects.

CRediT authorship contribution statement

Sepideh Ghalambaz: Visualization, Formal analysis, Conceptualization, Methodology, Data curation, Software, Validation, Writing – original draft, Writing – review & editing, Supervision. **Ahmad Hajjar:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Obai Younis:** Methodology, Writing – review & editing, Investigation. **Ammar Alsabery:** Methodology, Writing – original draft, Writing – review & editing. **Mohammad Ghalambaz:** Visualization, Formal analysis, Conceptualization, Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial

Table 7
Top-10 countries with the highest link strength.

R	Country	Documents	Citations	Total link strength
1	Pakistan	645	9494	860,809
2	Saudi Arabia	566	8882	806,616
3	India	651	5570	771,107
4	Iran	335	8739	427,924
5	China	310	5001	409,579
6	Malaysia	152	2083	290,084
7	Egypt	213	2287	281,232
8	Vietnam	138	2799	248,851
9	Turkey	116	1636	175,979
10	Romania	81	1316	172,784

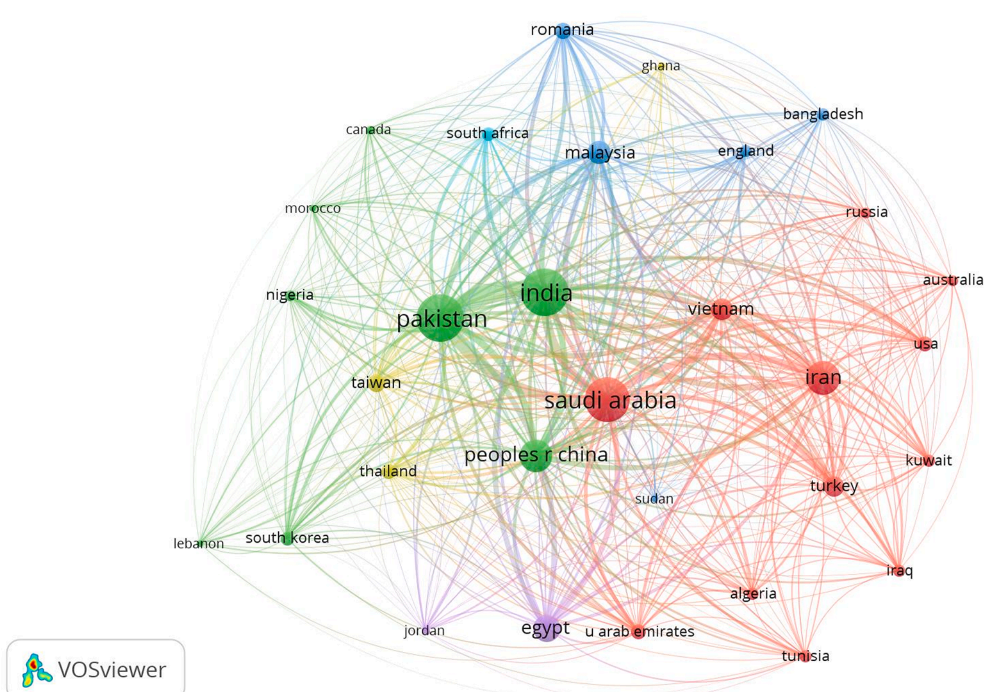


Fig. 11. Country bibliographic coupling in MNF. A minimum threshold of 10 publications with 200 links.

Table 8
Top 15 publications concerning their total citations (TC).

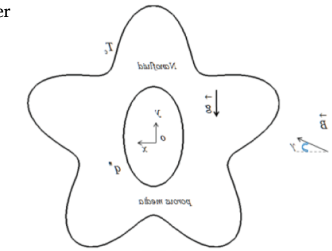
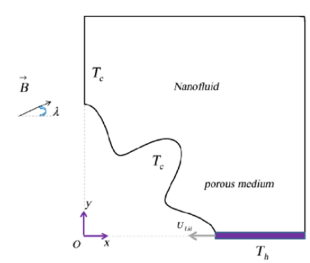
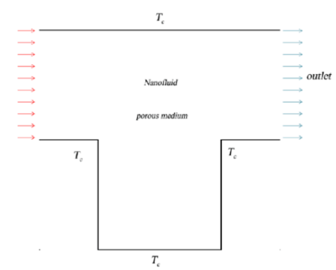
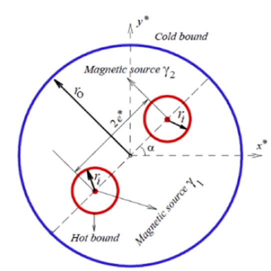
R	Ref.	CA*	Year	TC	Title	Schematic
1	[36]	Sheikholeslami, M.	2019	448	"Numerical approach for MHD al2o3-water nanofluid transportation inside a permeable medium using innovative computer method". Image with permission from Elsevier.	
					Sheikholeslami numerically evaluated the natural convection heat transfer of a water-alumina nanofluid in the presence of a uniform magnetic field, radiant heat transfer, and Brownian motion within a porous medium with complex geometry (starfish). Darcy model is used to model the porous medium. The results were shown in dimensionless numbers and parameters such as nanoparticle volume fraction, radiation parameter, and Rayleigh and Hartmann numbers. The results show that increasing the MNF number and the radiation parameter improves the heat transfer rate, but increasing the Hartmann number reduces the heat transfer rate.	
2	[37]	Sheikholeslami, M.	2018	226	"CuO-water nanofluid flow due to magnetic field inside a porous medium considering Brownian motion". Image with permission from Elsevier.	
					Sheikholeslami investigated the forced convection heat transfer of homogeneous water-copper oxide nanofluids in the presence of a uniform magnetic field and Brownian motion. A square porous medium with the bottom-left sides gathered was considered. The non-Darcy model was used for the porous medium. The results showed that more thermal gradients are created by increasing the permeability. Also, it is possible to achieve the highest heat transfer rate by using flat nanoparticles.	
3	[38]	Sheikholeslami, M.	2018	198	"Numerical investigation for CuO-H2O nanofluid flow in a porous channel with magnetic field using the mesoscopic method". Image with permission from Elsevier.	
					Sheikholeslami is considered a saturated T-shaped chamber of a porous medium and water-copper oxide nanofluid. The hot fluid enters the chamber from the left, under the influence of the considered boundary conditions, exchanges heat, and leaves the chamber with a decrease in temperature relative to the inlet. In this research, like other studies of Sheikholeslami, a uniform magnetic field has been used. The Lattice-Boltzmann method was used to solve the problem. The results showed that with increasing Lorentz force, the speed decreases.	
4	[39]	Sheremet, M. A.	2019	181	"Variable magnetic forces impact on magnetizable hybrid nanofluid heat transfer through a circular cavity". Image with permission from Elsevier.	

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Table 8 (*continued*)

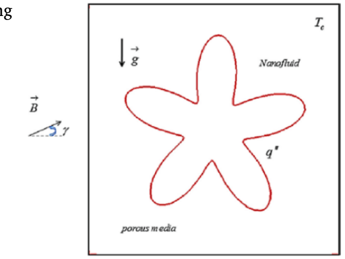
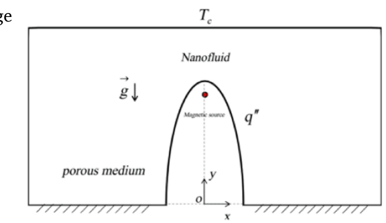
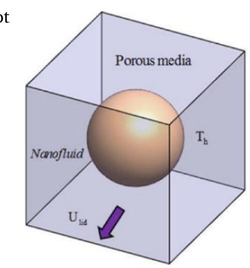
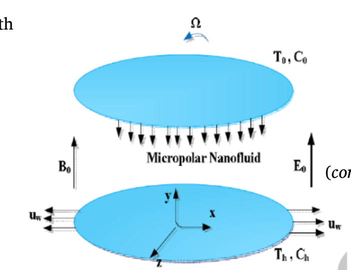
R	Ref.	CA*	Year	TC	Title	Schematic
Sheikholeslami et al. evaluated both the hydrodynamic and magnetohydrodynamic effects around a multilayer water-iron oxide/carbon nanotube hybrid nanofluid. For this purpose, a closed circular chamber was considered. The chamber is simple and does not have a porous medium. The results showed that increasing the volume fraction of nanoparticles improves the heat transfer rate (Nusselt number).						
5	[40]	Sheikholeslami, M.	2018	181	"Numerical modeling for alumina nanofluid magnetohydrodynamic convective heat transfer in a permeable medium using Darcy law". Image with permission from Elsevier.	
Using the Darcy model, the natural heat transfer of water-alumina nanofluid inside a square chamber was evaluated. Inside the chamber, the source of internal heat production was considered to be a starfish. Due to the adopted boundary conditions, the closed chamber was symmetrical with respect to the vertical axis. Also, the fluid flow was affected by the uniform magnetic field and the radiation effects. Maxwell's base relation is used for effective thermal conductivity, and Brinkman's relation with Brownian motion is used for effective dynamic viscosity coefficient. The results show that with increasing Rayleigh number and the effects of radiation, the average Nusselt number increases, while the number decreases with increasing Hartmann's number.						
6	[41]	Sheikholeslami M. and Shehzad, S. A	2018	170	"Numerical analysis of Fe3O4-H2O nanofluid flow in permeable media under the effect of external magnetic source". Image with permission from Elsevier.	(a)
In their research, Sheikholeslami and Shehzad evaluated the effect of a local and uniform magnetic field on water-iron oxide nanofluids. They introduced a rectangular chamber saturated with a porous medium while a half-diameter oval with a larger diameter was reduced vertically from the chamber. The effect of radiant heat transfer was also considered in their work. The results were evaluated for different values of Rayleigh, Darcy, Hartmann, and radiation parameters. The results showed that the heat transfer rate (Nusselt number) decreases with increasing Hartmann number.						
7	[42]	Sheikholeslami, M.	2018	168	"Influence of magnetic field on al2o3-h2o nanofluid forced convection heat transfer in a porous lid-driven cavity with hot sphere obstacle by means of LBM.". Image with permission from Elsevier.	
Sheikholeslami evaluated the forced heat transfer of water-alumina homogeneous nanofluids within a three-dimensional closed chamber in a three-dimensional numerical study. Inside the chamber, a spherical body with internal heat generation was used. The Lattice-Boltzmann method was used to solve the problem. Like other studies of Sheikholeslami, the uniform magnetic field affects the fluid flow. The results show that the heat transfer rate improves by amplifying the Reynolds and Darcy numbers. But the effect of the Hartmann number on the average Nusselt number is negative.						
8	[43]	Bonyah, E.	2018	141	"The electrical MHD and hall current impact on the micropolar nanofluid flow between rotating parallel plates". Image with permission from Elsevier.	

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Table 8 (*continued*)

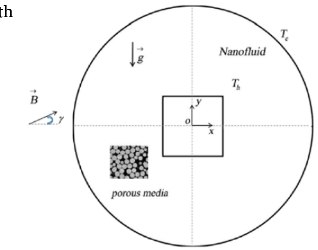
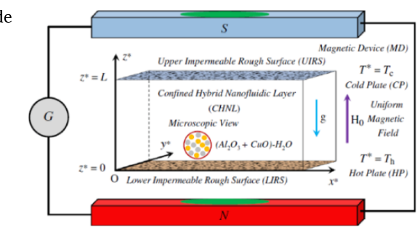
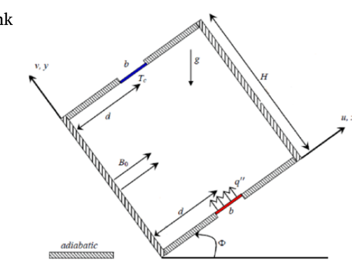
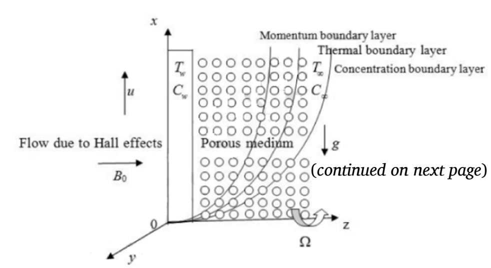
<table>
<tr><th>R</th><th>Ref.</th><th>CA*</th><th>Year</th><th>TC</th><th>Title</th><th>Schematic</th></tr>
<tr><td colspan="7">The nanofluid flow between two rotating horizontal parallel plates was evaluated in the presence of a magnetohydrodynamic effect by Shah et al. The nanofluid is heterogeneous, and the effects of Brownian motion and thermophoresis are included in the governing equations. An analytical method was used to solve the equations. The results show that the flow distribution and nanoparticle concentration are improved by increasing the thermophoresis parameter. Also, as the rotational parameter increases, the motion of the fluid also improves.</td></tr>
<tr><td>9</td><td>[44]</td><td>Sheikholeslami, M. and Rokni, H.B.</td><td>2018</td><td>141</td><td>“Magnetic nanofluid flow and convective heat transfer in a porous cavity considering Brownian motion effects”. Image with permission from AIP Publishing.</td><td>
</td></tr>
<tr><td colspan="7">Sheikholeslami and Rokni evaluated the natural heat transfer of a nanofluid in a circular porous medium. A square with specified dimensions is reduced from the proposed geometry center. Their research considered the effects of a uniform magnetic field and the Brownian motion of nanoparticles. Water and copper oxide formed the base fluid and nanoparticles, respectively. There was a local thermal imbalance between the nanofluid and the porous solid matrix. The results were presented symmetrically to the vertical axis. Sheikholeslami and Rokni found that the mean Nusselt number is inversely proportional to the porosity coefficient, the Hartmann number, and the interface heat transfer parameter between the nanofluid phases and the porous solid matrix.</td></tr>
<tr><td>10</td><td>[31]</td><td>Wakif, A.</td><td>2021</td><td>138</td><td>“Thermal radiation and surface roughness effects on the thermo-magneto-hydrodynamic stability of alumina-copper oxide hybrid nanofluids utilizing the generalized Buongiorno’s nanofluid model”. Image with permission from Springer.</td><td>
</td></tr>
<tr><td colspan="7">Wakif et al. Investigated the stability of copper-alumina oxide nanoparticles in a water-based fluid using the Buongiorno method. The hybrid nanofluid in the space between the two permeable flat plates was affected by radiant heat transfer, uniform magnetic field, and surface roughness. The results showed that the water-copper-alumina hybrid nanofluid would be less stable despite the effects of thermophoresis and Brownian motion. On the other hand, with a significant increase in roughness, the stability of the hybrid nanofluid will improve.</td></tr>
<tr><td>11</td><td>[33]</td><td>Armaghani, T.</td><td>2018</td><td>132</td><td>“Entropy generation and MHD natural convection of a nanofluid in an inclined square porous cavity: effects of a heat sink and source size and location”. Image with permission from Elsevier.</td><td>
</td></tr>
<tr><td colspan="7">The heat transfer of a homogeneous nanofluid inside a closed square chamber with a certain angle of deviation from the horizontal axis in the presence of a uniform magnetic field and a well and a heat source has been evaluated by Rashad et al. Maxwell, and Brinkmann equations were used to determine the ratio of effective thermal conductivity and dynamic viscosity, respectively. One of the goals of the authors was to study the production of entropy in the presence of a uniform magnetic field. The results in the form of dimensionless numbers showed that the maximum rate of heat transfer occurred approximately at angles of deviation of 50 and 310 degrees. Also, as Hartmann’s number increases, entropy production decreases.</td></tr>
<tr><td>12</td><td>[32]</td><td>Krishna, M.V.</td><td>2019</td><td>131</td><td>“Hall and ion slip effects on MHD rotating boundary layer flow of nanofluid past an infinite vertical plate embedded in a porous medium”. Image with permission from Elsevier.</td><td>
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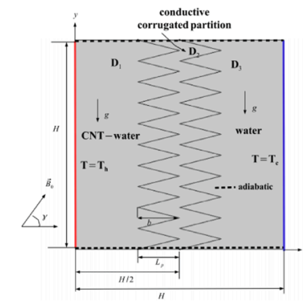
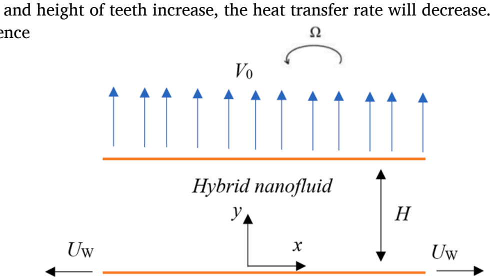
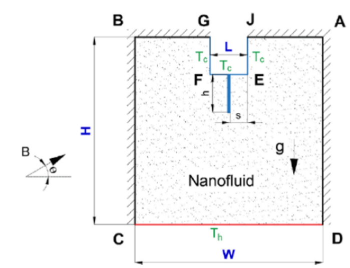
Table 8 (*continued*)

R	Ref.	CA*	Year	TC	Title	Schematic
The thermal-mass boundary layer of water-silver and water-titania nanofluids in the vicinity of a porous medium leading to a vertical wall was investigated by Krishna and Chamkha. The vertical wall had a certain velocity, temperature, and concentration, while the uniform magnetic field was considered perpendicular to the wall. Maxwell and Brinkman's relations were considered effective for thermal conductivity and dynamic viscosity ratios. The governing equations also include the effects of radiant heat transfer and chemical reactions. They showed that the heat transfer rate decreases with increasing radiation, deflection, and suction parameters. Also, the chemical reaction and suction parameters increase the Sherwood number.						
13	[45]	Selimefendigil, F.	2019	124	"Corrugated conductive partition effects on MHD free convection of CNT-water nanofluid in a cavity". Image with permission from Elsevier.	
Selimefendigil and Oztop investigated the natural heat transfer of a homogeneous water-carbon nanotube nanofluid in a closed square chamber. Tooth-toothed partitions were included inside the chamber. The chamber was exposed to a uniform magnetic field. They found that using 3% nanoparticles in the base fluid improved the heat transfer rate by up to 84% compared to the base fluid. Also, as the number and height of teeth increase, the heat transfer rate will decrease.						
14	[34]	Dogonchi, A.S.	2019	119	"Magnetohydrodynamic flow and heat transfer of a hybrid nanofluid in a rotating system among two surfaces in the presence of thermal radiation and Joule heating"	
Chamkha et al. Considered two rotating flat plates and used water-copper and graphene oxide hybrid nanofluids in the space between them. The effects of viscosity, radiation, uniform magnetic field, and rotation of the plates were evaluated in terms of mold, acre number, radiation parameter, magnetic number, and rotation parameter in suction and injection modes, respectively. The results showed that the heat transfer rate improves with increasing the radiation parameter, while it increases with increasing the magnetic number and the rotational parameter.						
15	[46]	Mohebbi.R. and Sheremet, M. A.	2019	116	"Numerical study of MHD nanofluid natural convection in a baffled u-shaped enclosure". Image with permission from Elsevier.	
The natural heat transfer of a homogeneous nanofluid inside a closed rectangular chamber in the presence of a tooth on its upper side was evaluated by Ma et al. The tooth is located in the form of a recess in the upper side of the chamber to which a vertical heating vane is attached. A uniform magnetic field with different angles affects the fluid flow. Lattice Boltzmann method was used to solve the governing equations. The results are presented for different values of the Rayleigh number as well as the corresponding ratio (indented tooth dimensions to overall chamber dimensions). They showed that as the Rayleigh number increases, the heat transfer rate increases. While changing the value of the corresponding ratio in the range of 0.2 to 0.6, the flow pattern is not affected.						

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interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

[1] O. Mahian, L. Kolsi, M. Amani, P. Estellé, G. Ahmadi, C. Kleinstreuer, J.S. Marshall, M. Siavashi, R.A. Taylor, H. Niazmand, Recent advances in modeling and simulation of nanofluid flows-Part I: Fundamentals and theory, Phys. Rep. 790 (2019) 1–48.

[2] O. Mahian, L. Kolsi, M. Amani, P. Estellé, G. Ahmadi, C. Kleinstreuer, J.S. Marshall, R.A. Taylor, E. Abu-Nada, S. Rashidi, Recent advances in modeling and simulation of nanofluid flows-part II: applications, Phys. Rep. 791 (2019) 1–59.

[3] B. M'hamed, N.A.C. Sidik, M.N.A.W.M. Yazid, R. Mamat, G. Najafi, G. Kefayati, A review on why researchers apply external magnetic field on nanofluids, International Communications in Heat and Mass Transfer, 78 (2016) 60-67.

[4] I. Torres-Díaz, C. Rinaldi, Recent progress in ferrofluids research: novel applications of magnetically controllable and tunable fluids, Soft Matter 10 (2014) 8584–8602.

[5] C. Scherer, A.M. Figueiredo Neto, Ferrofluids: properties and applications, Brazilian J. Physics 35 (2005) 718–727.

[6] M. Kole, S. Khandekar, Engineering applications of ferrofluids: A review, J. Magnetism Magnetic Materials 537 (2021), 168222.

[7] S. Papell, Low viscosity magnetic fluid obtained by the colloidal suspension of magnetic particles Patent, (1965).

[8] A.J. Chamkha, S.K. Jena, S.K. Mahapatra, MHD convection of nanofluids: a review, J. Nanofluids 4 (2015) 271–292.

[9] M. Sheikholeslami, H.B. Rokni, Simulation of nanofluid heat transfer in presence of magnetic field: a review, Int. J. Heat Mass Transfer 115 (2017) 1203–1233.

[10] S.O. Giwa, M. Sharifpur, M.H. Ahmadi, J.P. Meyer, Magnetohydrodynamic convection behaviours of nanofluids in non-square enclosures: a comprehensive review, Math. Methods Applied Sciences (2020).

[11] G. Wang, Z. Zhang, R. Wang, Z. Zhu, A review on heat transfer of nanofluids by applied electric field or magnetic field, Nanomaterials 10 (2020) 2386.

[12] I. Nkurikiyimfura, Y. Wang, B. Safari, E. Nshingabigwi, Electrical and thermal performances of photovoltaic/thermal systems with magnetic nanofluids: A review, Particuology 54 (2021) 181–200.

[13] A. Kumar, S. Subudhi, Preparation, characteristics, convection and applications of magnetic nanofluids: A review, Heat Mass Transf. 54 (2018) 241–265.

[14] S. Doganay, R. Alsangur, A. Turgut, Effect of external magnetic field on thermal conductivity and viscosity of magnetic nanofluids: A review, Mater. Res. Express 6 (2019), 112003.

[15] Z. Liu, Y. Yan, R. Fu, M. Alsaady, Enhancement of solar energy collection with magnetic nanofluids, Thermal Sci. Engineering Progress 8 (2018) 130–135.

[16] N.S. Khashi'ie, N.M. Arifin, R. Nazar, E.H. Hafidzuddin, N. Wahi, I. Pop, Magnetohydrodynamics (MHD) axisymmetric flow and heat transfer of a hybrid nanofluid past a radially permeable stretching/shrinking sheet with Joule heating, Chinese J. Physics 64 (2020) 251–263.

[17] S. Mansur, A. Ishak, I. Pop, MHD homogeneous-heterogeneous reactions in a nanofluid due to a permeable shrinking surface, J. Appl. Fluid Mechanics 9 (2016) 1073–1079.

[18] F.M. Ali, R. Nazar, N.M. Arifin, I. Pop, Dual solutions in MHD flow on a nonlinear porous shrinking sheet in a viscous fluid, Boundary Value Problems 2013 (2013) 1–7.

[19] N.S. Khashi'ie, N. Md Arifin, R. Nazar, E.H. Hafidzuddin, N. Wahi, I. Pop, A stability analysis for magnetohydrodynamics stagnation point flow with zero nanoparticles flux condition and anisotropic slip, Energies, 12 (2019) 1268.

[20] M. Izadi, M.A. Sheremet, S. Mehryan, I. Pop, H.F. Öztop, N. Abu-Hamdeh, MHD thermogravitational convection and thermal radiation of a micropolar nanoliquid in a porous chamber, Int. Commun. Heat Mass Transfer 110 (2020), 104409.

[21] M.A. Sheremet, M.S. Astanina, I. Pop, MHD natural convection in a square porous cavity filled with a water-based magnetic fluid in the presence of geothermal viscosity, Int. J. Numer. Meth. Heat Fluid Flow (2018).

[22] M. Sheremet, T. Grosan, I. Pop, MHD free convection flow in an inclined square cavity filled with both nanofluids and gyrotactic microorganisms, Int. J. Numer. Meth. Heat Fluid Flow (2019).

[23] M.A. Sheremet, H. Oztop, I. Pop, K. Al-Salem, MHD free convection in a wavy open porous tall cavity filled with nanofluids under an effect of corner heater, Int. J. Heat Mass Transf. 103 (2016) 955–964.

[24] M.S. Astanina, M.A. Sheremet, H.F. Oztop, N. Abu-Hamdeh, MHD natural convection and entropy generation of ferrofluid in an open trapezoidal cavity partially filled with a porous medium, Int. J. Mech. Sci. 136 (2018) 493–502.

[25] M.A. Sheremet, H. Oztop, I. Pop, MHD natural convection in an inclined wavy cavity with corner heater filled with a nanofluid, J. Magn. Magn. Mater. 416 (2016) 37–47.

[26] F. Selimefendigil, H.F. Öztop, A.J. Chamkha, MHD mixed convection and entropy generation of nanofluid filled lid driven cavity under the influence of inclined magnetic fields imposed to its upper and lower diagonal triangular domains, J. Magn. Magn. Mater. 406 (2016) 266–281.

[27] F. Selimefendigil, H.F. Öztop, Numerical study of MHD mixed convection in a nanofluid filled lid driven square enclosure with a rotating cylinder, Int. J. Heat Mass Transf. 78 (2014) 741–754.

[28] R. Dhanai, P. Rana, L. Kumar, MHD mixed convection nanofluid flow and heat transfer over an inclined cylinder due to velocity and thermal slip effects: Buongiorno's model, Powder Technol. 288 (2016) 140–150.

[29] M.A. Sheremet, I. Pop, N.C. Roşca, Magnetic field effect on the unsteady natural convection in a wavy-walled cavity filled with a nanofluid: Buongiorno's mathematical model, J. Taiwan Inst. Chem. Eng. 61 (2016) 211–222.

[30] M.H.d.M. Rodrigues, J.B. Souza Junior, E.R. Leite, The Influence of Magnetic Field and Nanoparticle Concentration on the Thin Film Colloidal Deposition Process of Magnetic Nanoparticles: The Search for High-Efficiency Hematite Photoanodes, Nanomaterials, 12 (2022) 1636.

[31] A. Wakif, A. Chamkha, T. Thumma, I. Animasaun, R. Sehaqui, Thermal radiation and surface roughness effects on the thermo-magneto-hydrodynamic stability of alumina–copper oxide hybrid nanofluids utilizing the generalized Buongiorno's nanofluid model, J. Therm. Anal. Calorim. 143 (2021) 1201–1220.

[32] M.V. Krishna, A.J. Chamkha, Hall and ion slip effects on MHD rotating boundary layer flow of nanofluid past an infinite vertical plate embedded in a porous medium, Results Phys. 15 (2019), 102652.

[33] A. Rashad, T. Armaghani, A.J. Chamkha, M. Mansour, Entropy generation and MHD natural convection of a nanofluid in an inclined square porous cavity: effects of a heat sink and source size and location, Chin. J. Phys. 56 (2018) 193–211.

[34] A.J. Chamkha, A. Dogonchi, D. Ganji, Magneto-hydrodynamic flow and heat transfer of a hybrid nanofluid in a rotating system among two surfaces in the presence of thermal radiation and Joule heating, AIP Adv. 9 (2019), 025103.

[35] S. Cole, Cole, J., Social Stratification in Science, University of Chicago Press, , Chicago, 1973.

[36] M. Sheikholeslami, Numerical approach for MHD Al2O3-water nanofluid transportation inside a permeable medium using innovative computer method, Comput. Methods Appl. Mech. Eng. 344 (2019) 306–318.

[37] M. Sheikholeslami, CuO-water nanofluid flow due to magnetic field inside a porous media considering Brownian motion, J. Mol. Liq. 249 (2018) 921–929.

[38] M. Sheikholeslami, Numerical investigation for CuO-H2O nanofluid flow in a porous channel with magnetic field using mesoscopic method, J. Mol. Liq. 249 (2018) 739–746.

[39] M. Sheikholeslami, S. Mehryan, A. Shafee, M.A. Sheremet, Variable magnetic forces impact on magnetizable hybrid nanofluid heat transfer through a circular cavity, J. Mol. Liq. 277 (2019) 388–396.

[40] M. Sheikholeslami, S. Shehzad, Z. Li, A. Shafee, Numerical modeling for alumina nanofluid magnetohydrodynamic convective heat transfer in a permeable medium using Darcy law, Int. J. Heat Mass Transf. 127 (2018) 614–622.

[41] M. Sheikholeslami, S. Shehzad, Numerical analysis of Fe3O4–H2O nanofluid flow in permeable media under the effect of external magnetic source, Int. J. Heat Mass Transf. 118 (2018) 182–192.

[42] M. Sheikholeslami, Influence of magnetic field on Al2O3-H2O nanofluid forced convection heat transfer in a porous lid driven cavity with hot sphere obstacle by means of LBM, J. Mol. Liq. 263 (2018) 472–488.

[43] Z. Shah, S. Islam, T. Gul, E. Bonyah, M.A. Khan, The electrical MHD and hall current impact on micropolar nanofluid flow between rotating parallel plates, Results Phys. 9 (2018) 1201–1214.

[44] M. Sheikholeslami, H.B. Rokni, Magnetic nanofluid flow and convective heat transfer in a porous cavity considering Brownian motion effects, Phys. Fluids 30 (2018), 012003.

[45] F. Selimefendigil, H.F. Öztop, Corrugated conductive partition effects on MHD free convection of CNT-water nanofluid in a cavity, Int. J. Heat Mass Transf. 129 (2019) 265–277.

[46] Y. Ma, R. Mohebbi, M. Rashidi, Z. Yang, M.A. Sheremet, Numerical study of MHD nanofluid natural convection in a baffled U-shaped enclosure, Int. J. Heat Mass Transf. 130 (2019) 123–134.